ELECTRIC CENTRAL STATION DISTRIBUTION SYSTEMS

THEIR

DESIGN AND CONSTRUCTION

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PREFACE TO FIRST EDITION.

This volume is the result of a group of articles which appeared serially in the *Electrical Age* during the years 1908 and 1909, covering various phases of Central Station Distribution Work. The preparation of these articles was undertaken by the authors because of repeated requests from young engineers engaged in distribution work for information bearing on many of the details of their work.

While there were various treatises dealing with special subjects such as low-tension networks, transmission of power, storage batteries, etc., quite fully, there appeared to be no treatise covering the general field of distribution from the standpoint of American practice to which young engineers and students could be referred. The material of the original articles revised and somewhat extended is presented in this volume. Two chapters have been included for convenient reference at the close of the book, in which are compiled such tables as are likely to be needed by the distribution engineer, together with a brief outline of the laws of electric circuits. The treatment is based upon the assumption of a general knowledge of electrical theory such as is possessed by the more advanced students of engineering and by men in practical distribution engineering work. Much of the subject matter of the book is, however, of such a nature as to be easily grasped by practical men who have not had a full theoretical training.

Distribution problems are usually capable of more than one solution, and the decision as to which is best is often

determined by local conditions which cannot be made subservient to general rules. It is therefore difficult to generalize upon many phases of the subject, and frequent use has been made of such qualifying phrases as "in most cases," "usually" or "under some circumstances."

The subject matter has been treated entirely from the American point of view, as the book is intended for American Engineers. European methods differ so much from those followed in America, owing to differences in the conditions under which electric lighting properties are owned and operated there, that it was not felt that their consideration would be of especial value.

THE AUTHORS.

CHICAGO, 1910.

PREFACE TO SECOND EDITION.

THE rapid changes in the conditions under which electricity is distributed, and the progress made since the first appearance of this treatise have necessitated numerous changes and the addition of considerable new matter. The subject of urban transmission and high-tension distribution has been made the subject of a separate chapter. The chapters on overhead and underground construction have been expanded to include the progress made in recent years. The discussion of diversity factor has been broadened and supplemented by a brief statement of the relation of diversity to the cost of service, and to rate systems.

With a view to improving the logical sequence of presentation, much of the text has been re-arranged and re-written.

THE AUTHORS.

CHICAGO, ILL.,
Aug. 1st, 1916.

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ELECTRIC CENTRAL STATION DISTRIBUTION SYSTEMS.

CHAPTER I.

SYSTEMS OF DISTRIBUTION.

Series Systems. — The arc lamp was the first practical device for converting electrical energy into light. It was developed by Brush in Cleveland in 1876 and later by Thomson and Houston and others.

The early arc systems found a ready application in the lighting of city streets. The large areas to be covered by street-lighting circuits led naturally to the high voltage series system as the most economical in first cost.

Special direct-current generators equipped with automatic regulators to maintain the current constant as the number of lamps in circuit varied, were required.

The lamps were designed to burn carbon electrodes which were consumed after about twelve hours' burning with a current strength of about ten amperes. Later, seven-ampere generators and lamps were designed in response to a demand for a less expensive light, and arc-lighting systems were extended to general commercial lighting.

Following the year 1895, the enclosed arc lamp burning carbon electrodes in an inner globe, so designed that a very small supply of air could enter, was brought to a commercial stage of development. These lamps required trimming only after sixty to eighty hours' burning, and so permitted a reduction of 75 to 80 per cent in the expense of carbons and

lamp trimming labor. They therefore became standard and were substituted for open arc lamp systems very generally during the following decade.

During this period of change from open to enclosed lamps, advantage was taken of the use of alternating current for arc lighting purposes. The special direct-current generator was replaced by a transformer receiving energy at the standard system voltage and delivering it to the circuit at the voltage required to maintain a constant current of the desired strength at full load.

This resulted in a considerable saving in the cost of series lighting equipment, since the main generator capacity of the alternating current systems cost very much less per lamp than the relatively small series arc machines which were required for the direct current systems.

There was also a greatly reduced building expense since the floor space required for the shafting and belting of the numerous arc machines was excessive.

The series regulating equipment could be placed in substations in various parts of a large city, thus shortening the average length of arc lighting circuits.

In some cases where there was too large an equipment of the better types of arc machines installed to be scrapped, the shafting and belting were displaced by alternating current motors, each driving a pair of arc machines. These systems at first used direct current enclosed lamps, and later magnetite or flaming arc lamps. For a time, this gave them some advantage over the alternating current systems which could not use the high efficiency direct current lamps without adding rectifier equipment. Mercury arc rectifiers were installed for this purpose where it was desired to get this benefit.

With the development of suitable flaming arc lamps for 60 cycle alternating current service, the necessity for recti-

fying equipment disappeared, and the alternating current series system became the simplest and most economical form of series distribution.

This system may be used equally well for series incandescent lighting and has become standard for new installations.

Two general types of regulating equipment are in use for the purpose of maintaining a constant current. One consists of a transformer of sufficient capacity to carry several circuits, with a separate choke coil for each series circuit. The position of the choke coil is varied by weights in such a way as to make it automatically add the necessary amount of reactance to hold the current constant.

The other is a transformer with secondary coils arranged to be movable with respect to the primary. The position of the secondary is governed by the action of weights which are balanced against the magnetic force between primary and secondary coils in such a way as to hold the current constant. Each circuit has its own transformer in this system.

The choke-coil system has not been found satisfactory on account of the fact that when grounds develop at two points on any of the circuits, a part of the lamps are shunted out, and the location of trouble is difficult.

The use of a separate transformer for each circuit has therefore become standard for alternating-current series circuits.

Series alternating-current systems using enclosed lamps are operated at 4.5 to 7.5 amperes, 6.6 amperes being the most common current strength.

The rapid advance in the development of the tungsten incandescent lamp has brought this form of lighting into close competition with arc lamps for all kinds of street and public space lighting.

The tungsten lamp, by reason of the wide range of sizes of units in which it can be made, is found as readily adapt-

able to the lighting of business districts using the larger units as to the lighting of residence districts with smaller units.

Tungsten units of 300 to 500 watts have been substituted for 450 watt alternating current enclosed arc lamps effecting a saving in operating cost and a materially improved illumination.

The life and efficiency of these units has been notably increased on series circuits by the use of a small compensator coil in the hood of the lamp which steps the current up from the standard current strength of the circuit to about 20 amperes in the lamp filament.

In the lighting of business districts where great intensities are essential the tungsten lamp in sizes of 750 to 1000 watts has advantages over the arc lamp which are resulting in the displacement of the arc lamp for this service.

In residence and suburban districts where shade trees demand the use of units distributed more frequently, the smaller sizes are most economical.

Application of Series Systems. — Since the lamps supplied by a series circuit are operated at constant current, it follows that the voltage impressed upon the circuit terminals must be varied as energy consuming devices are switched into or out of the series. With circuits operated at 6.6 to 10 amperes, the pressure absorbed at the terminals of a 500 watt arc lamp is from 50 to 75 volts, and the circuit must be operated at 5000 to 7500 volts when carrying 100 of these lamps.

A constant current circuit is thus, inherently, a high potential circuit and is not suited to the requirements of safety and convenience afforded by low potential systems for the lighting of buildings.

The use of constant current systems for interior lighting which was common in the earlier years of the industry has

therefore steadily decreased, and following the introduction of the tungsten lamp, practically disappeared.

Series distribution has found a wide field of application in the field of street and park lighting. The conditions obtaining in such lighting are that the load density runs from 5 to 10 kw. per mile of street and the lights must be switched on and off at a given time each day.

The switching requirements favor the use of separate circuits, controlled at the point of supply.

On the contrary, the low load density favors the absorption of the street lighting load on the general lighting system as far as possible.

Where the general light and power system does not fully cover the district in which the streets are to be lighted or where alley routes are largely used, it is sometimes more economical to run separate circuits on the streets to be lighted. Where there is no general supply as in park and boulevard lighting, it is usually necessary to provide separate circuits in any event, in which case the series system is usually the more economical.

In the central parts of larger cities, street lighting is often supplied from the general system, the switching being done more economically by patrolmen.

Types of Series Circuits. — The routing of a series lighting circuit is fixed by

(*a*) the location of the lamps.

(*b*) the geographical arrangement of streets and alleys and

(*c*) the requirements of operation and maintenance.

Having the locations of the lamps fixed, the problem of circuit design consists in so routing the circuit that it will require a minimum length of conductor consistent with requirements of continuous service.

The series system is subject to the inherent weakness that

a break on any loop of the circuit interrupts the service on the entire circuit. With circuits having 5 to 10 miles of conductor the location of a break may require considerable time, during which several miles of streets are in darkness unless facilities for testing are provided at several points on the circuit.

A circuit may be laid out on the open loop plan as shown in Fig. 1, or on the parallel loop plan as in Fig. 2. The open loop

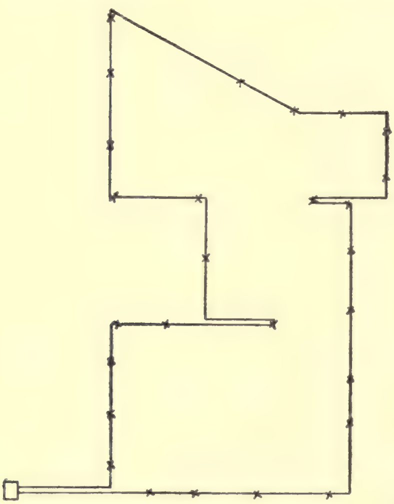


Fig. 1. Open Loop Series Circuit.

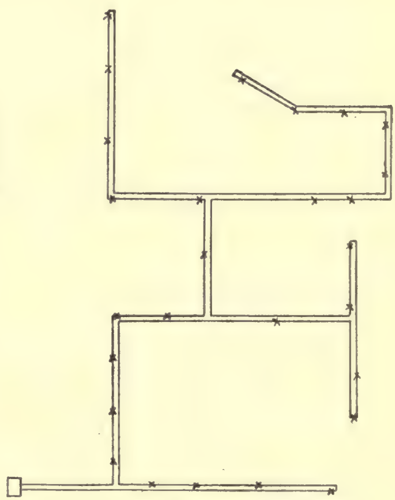


Fig. 2. Parallel Loop Series Circuit.

circuit proceeds away from the point of supply through one section of the city and returns through another district. Consisting of but one wire, it is constructed with the minimum of conductor mileage. But in case of a break there is no provision for making a test to locate the trouble, and the circuit must be traversed until the break is located.

With the parallel loop plan the wires are together so that a jumper connection can be made at any one of a number of points. When a break occurs the circuit can be quickly closed through the remaining lamps and only those lamps on

the broken loop are out. The provision of several test points on a circuit thus enables a repair man to locate the broken loop promptly and restore service on the remainder of the circuit before the break is repaired.

When continuity of service is important, the use of open loop should be limited to relatively small areas, as in Fig. 3, and the circuits should be equipped with convenient facilities

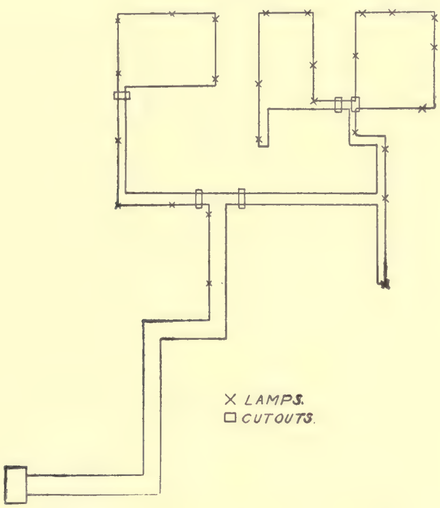


Fig. 3. Mixed Loop Series Circuit.

by which tests can be quickly made. With alternating current the use of extended open loops is likely to be the source of trouble with telephone and other signaling circuits.

Series Cutouts. — The type of switch required for the control of lamps or groups of lamps on a series circuit must be such that it will short-circuit the loop which is to be cut out, and remove the short-circuit when the loop is to be cut in. The capacity of the "cutout" as it is commonly known, is determined by its ability to open the short circuit across a

loop, without allowing the arc to carry across the terminals. Its current-carrying parts are ordinarily more than ample when made sufficiently rugged for mechanical strength.

It is desirable that the loop which is switched out be completely isolated from the working circuit, for the safety of repair men. The cutout is therefore usually so constructed as to both short-circuit and disconnect the loops and in this form is known as an "absolute" cutout.

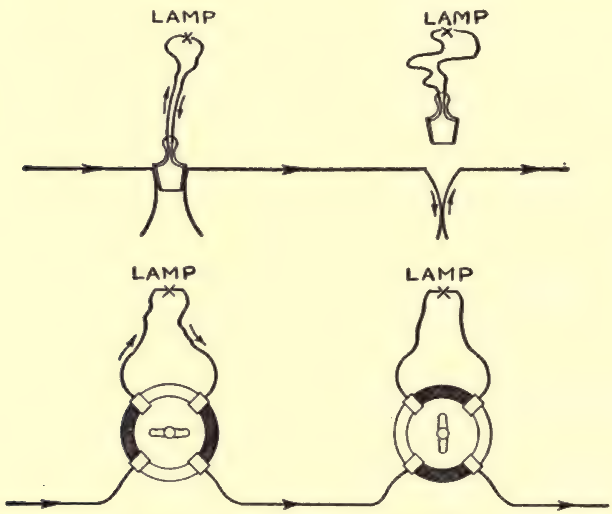


Fig. 4. Types of Series Cutouts.

Various mechanical arrangements have been devised by which loops can be absolutely cut out, two of the more common being shown in Fig. 4 as used in overhead construction. When lead covered cables are brought into the base of a lamp pole, a combination pothead and cutout such as that shown in Fig. 5 has been found very useful.

Constant Current Transmission. — The use of constant current has been limited to street lighting systems almost entirely in America. In France, however, M. Thury has

developed a system of generators and accessories which are being used to transmit energy over considerable distance at constant current strengths of 100 to 150 amperes, at 20,000 to 30,000 volts or more.

In these systems the power is delivered to the line from the generators connected in series at voltages as high as 10,000 volts each, and is received by series motors driving alternating current generators which supply the distributing system. The generating and sub-station machinery is necessarily more complicated and expensive than that required for an alternating current constant potential system, but the high tension switching equipment is very simple.

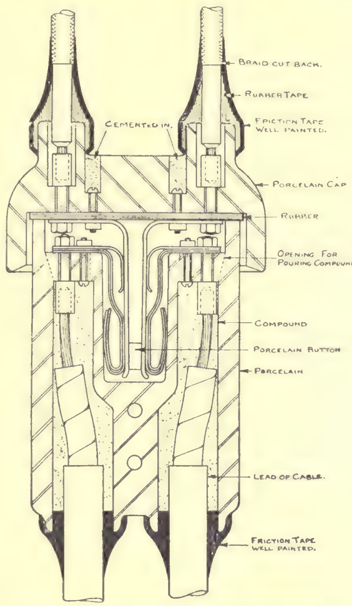


Fig. 5. Series Cutout. Pothead Type.

The simplicity of the switching equipment results in a material saving in space, which is said to largely offset the differences between the cost of the motor-generator equipment and the step down transformer equipment which would be used with an alternating current transmission system at equivalent transmission pressures.

The use of direct current in the series transmission system makes possible the use of somewhat less insulating material in the cable system for a given working voltage, as the maximum pressure at the peak of the wave is 40 per cent higher than it is in a direct current system at the same effective pressure. The weight of copper required for a series system working at the same effective pressure and percentage of loss

as a three-phase system is 33 per cent greater, since the three-phase circuit requires but 75 per cent as much copper as an equivalent single phase or direct current circuit. But by increasing the pressure in the series direct current system, 33 per cent the total weight of copper and thickness of insulation may be made the same as for an equivalent three-phase circuit. The series circuit has the further advantage that there are but two conductors to insulate as against three in the three-phase circuit.

Series transmission is obviously not so well suited to conditions where it is desirable to take off branches for industrial power consumers or for smaller towns, as is alternating transmission.

Multiple Systems. — The comparatively large unit required for arc lighting rendered it unfit for interior lighting of many kinds and led to a demand for a "subdivided" form of light, which could be used in houses, offices and stores, as a substitute for gas and oil lamps. The high voltages inherent to series systems made them unsafe to life and property, and suggested the desirability of a multiple system operating at a voltage low enough to be safe and easy to handle, and yet high enough to be commercially feasible.

These considerations led Thos. A. Edison to enter upon a long and most thorough search for materials which could be made into an incandescent type of lamp. His untiring zeal and native genius finally produced incandescent lamps which would burn for a sufficient length of time to be considered commercially practicable.

Having solved the problem of subdividing the electric lamp, he next turned his attention to the development of a multiple system of distribution by which it could be made available to the world. This involved a suitable lamp socket and base,

safety fuse cutouts to protect from short circuits, switches of all sizes, generators, motors, and various wiring fittings none of which were then available.

The necessity of using underground construction further required the development of the "tube" system of mains and feeders, together with junction boxes and fittings.

The first electric central station for incandescent lighting in America was put into operation in August, 1882, at Appleton, Wisconsin. This was followed within a few weeks by the first station of the Edison Illuminating Company of New York. These first systems were operated at about 110 volts on the two-wire plan. Direct current was used because of the lack of knowledge of alternating-current motors and transformers, and the ready adaptability of the direct-current motor to variable-speed machinery.

The voltage was fixed at about 110 by the inherent nature of the incandescent lamp filament, which in the early stages of the art could not be made to give 16 candle power at much more than 110 volts without reducing the life of the filament below commercial limits.

The excessive cross-section of copper used to deliver electricity in the quantities demanded and at the distances required led Edison to devise his three-wire system. This system which is widely used at present is based on the operation of two generators in series with a third wire connected between the machines. This permitted the use of 110-volt lamps and yet gave the advantage of 220-volt distribution when the load was evenly divided on the opposite sides of the third or neutral wire. Its invention permitted a saving in conductor copper of over 60 per cent and doubled the radius of distribution.

This system was adopted for use in the central parts of most of the larger American cities and in many of the cities of Europe, and was designed for installation underground, since municipal regulations required it in most large cities.

The adaptability of the direct-current motor to elevator and other variable-speed power work, and the possibility of utilizing the storage battery as a reserve in case of emergency, have made it desirable to retain the direct-current systems in the central parts of most of the larger cities where it was originally established.

The excessive investment required to extend low potential lines into the parts of a city where the load is scattered and the necessity of establishing several generating stations in the large cities, thus increasing the cost of operation, led inventors to turn their attention to the development of alternating-current distributing systems by which higher voltages could be used with transformers. The first alternating-current system was put into operation at Greenburg, Pennsylvania, in 1886, by the Westinghouse Company. Thomson and Houston added an alternating-current system to their series arc system which had been very successful, and others followed.

These systems were designed to operate at 125 to 133 cycles, 1100 volts, single-phase, and were installed in medium-sized cities where the direct current had not been established, or in the outlying parts of those cities which were being served with direct current in their central portions.

As these systems developed, the demand for power service became greater and the plants needed a day load to make them profitable. The single-phase motor was not satisfactory at 125 cycles in any except the smaller sizes, and the alternating-current systems were greatly handicapped on this account. In 1888, Tesla brought out his polyphase system, in which two, three or more single-phase circuits were arranged to operate with a definite phase displacement between them. This permitted the use of a simple form of self-starting motor which could be made in any desired size. Being of a rugged character its maintenance was less expensive than that of the direct-current and other commutator types of motors.

The Tesla system was introduced in America by Westinghouse. His engineers selected the two-phase system as being the best suited to general distribution work, chiefly because the problem of balancing two phases in a small system presented the fewest difficulties.

Experience had previously demonstrated that 1100 volts was too low for satisfactory service in the larger systems and 2200 volts was therefore made standard.

The design of polyphase motors was found to be much more satisfactory at 60 cycles than at 125, and this was true of arc lamps and other apparatus having coil windings. The two-phase system was therefore developed for 2200 volts and 60-cycle operation.

The three-phase system was used at first only in the transmission of large amounts of power at higher voltages than were used in distribution work.

Where two-phase generators constituted the source of supply the energy was transformed into three-phase for the purpose of transmission by a special method of connections devised by Charles F. Scott of the Westinghouse Company.

Later the three-phase system was made more generally available and was adopted for distribution in some of the larger cities where the problem of balancing was not difficult because of the larger loads involved. Thus it came about that both two-phase and three-phase distribution systems are in use in the larger American cities.

The value of three-phase transmission for large amounts of energy was soon recognized by the engineers of the larger direct-current systems, who were in need of some means of consolidating numerous small steam plants into one or two large generating stations, to reduce the cost of production. This was accomplished by the introduction of rotary converter substations receiving high-tension three-phase energy

and converting it to direct current at 110–120 volts for distribution.

The first American installation of this character was designed by Louis A. Ferguson and was put into operation in Chicago in the year 1897. It was operated at 2250 volts, and 25-cycles, three phase, and carried a load of about 200 k.w. permitting a steam plant to be shut down except during the heavy load period in the evening.

This was very shortly raised to 4500 volts and later to 9000 volts as the system was extended.

The 25-cycle frequency was adopted because of the more satisfactory operation of synchronous converters at the lower frequencies, and this became standard for systems where the larger part of the energy was converted to direct current for distribution.

It was too low, however, for use with arc and incandescent lamps directly and the adoption of 60-cycles as a standard frequency for alternating-current distribution rendered it necessary to provide motor generator sets as the converting medium where alternating current supply was derived from a 25-cycle transmission system.

These frequency changer sub-stations were later supplemented in some of the larger cities by transformers supplied from a separate 60-cycle generating system. The lower efficiency and higher first cost of frequency changing sets as compared with transformers made it desirable to establish separate generating and transmission systems for the 60-cycle supply as soon as the 60-cycle portion of the load became large enough to justify an economical size of generating unit.

Various transmission voltages were adopted, 6600 being used in New York, 9000 in Chicago and 13,200 in some of the other large cities. In Boston, Chicago and other cities voltages of 20,000 and upward were later adopted for use in transmission to suburban districts. As a result of this grad-

ual development several systems of distribution are found in general use in American cities, the advantages and disadvantages of which will be considered.

Single-Phase. — This is a two-wire system and therefore the simplest to install and maintain of the alternating-current systems. When used for distribution in cities it is commonly

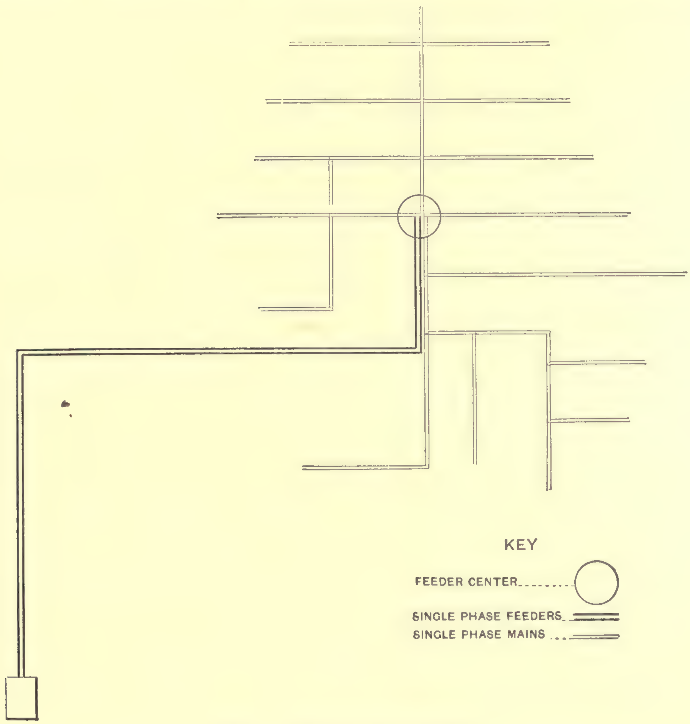


Fig. 6. Single-phase Feeder.

operated at 2200 volts and 60 cycles, though some of the early 1100-volt, 125-cycle systems are still in operation.

The investment required for feeder copper is 33 per cent more than for a three-phase feeder, other things being equal. This is true of the distributing mains only where there is a

high load density, that is, where the load is sufficient to require the use of primary mains larger than No. 6 A.W.G. The mains must be of a minimum size for mechanical strength (usually No. 6 or No. 4) and in scattered districts, the third wire required for a three-phase system adds 50 per cent to the cost of copper if three wire or 100 per cent if four wire without a commensurate gain in efficiency of distribution.

The use of single-phase distribution in such districts is also most economical from the standpoint of transformer investment. The division of a scattered lighting load between three phases decreases the average size of transformers, thus increasing the investment and iron losses.

It is therefore usual to retain the advantages of single-phase distribution in polyphase systems by making the branches which supply no large power, single-phase.

The chief limitation of single-phase distribution as applied to all purposes is that single-phase motors are much more complicated and expensive than polyphase motors and their use is limited to the smaller sizes. A single-phase feeder is shown in Fig. 6.

Two-phase Systems. — In two-phase systems the generator delivers two separate currents, one of which is a quarter cycle behind the other. Hence the name quarter-phase is sometimes applied to these systems.

When the two parts of the system are operated electrically separated from each other, four wires are required. Under these conditions the circuits are virtually single-phase as far as their capacity for the transmission of energy is concerned. Where used to supply the windings of a two-phase motor through suitable transformers, the displaced phase produces a torque which makes the motor self-starting without special commutation or split phase coils, such as are necessary with single-phase motors.

Where used for general lighting and power distribution, the lighting taps are made single-phase and balanced on the two phases with approximate equality. The four wires are carried along the principal thoroughfares and in such other places as the demand for large power service requires. Consumers using less than 5 horse power are usually required to provide single-phase motors, on account of the extra cost of transformers and line wire required for small two-phase service.

With inductive loads the drop on the two phases is not symmetrical and this tends to produce an unbalanced pressure condition on motor circuits.

The two-phase system requires but two transformers for power service. In this respect it has an advantage over the three-phase system. Where the amount of power served is less than 25 to 30 horse power, two transformers may be used in either the two-phase or the three-phase system, but in larger installations, there is a saving in transformer investment in two-phase installations due to the average size of units being larger and to the ability to adjust transformer capacity to maximum demand somewhat more closely. Thus in a two-phase installation, a demand of 85 kv-a. could be taken care of by 2–40 kv-a. units while in three-phase work, this load would ordinarily require 3–30 kv-a. units, costing about 20 per cent more than the two-phase installation.

One method of arrangement of a four-wire two-phase feeder supplying a mixed light and power load is shown in Fig. 7. Where two terminals of a two-phase generator are connected together, as shown in Fig. 8, two of the four wires may be combined in one neutral wire and the feeder and main system reduced to a three-wire basis.

The neutral wire in such a system carries the resultant of the current in the two phases, which is 41.4 per cent more than that in the phase wires. That is, in a feeder carrying

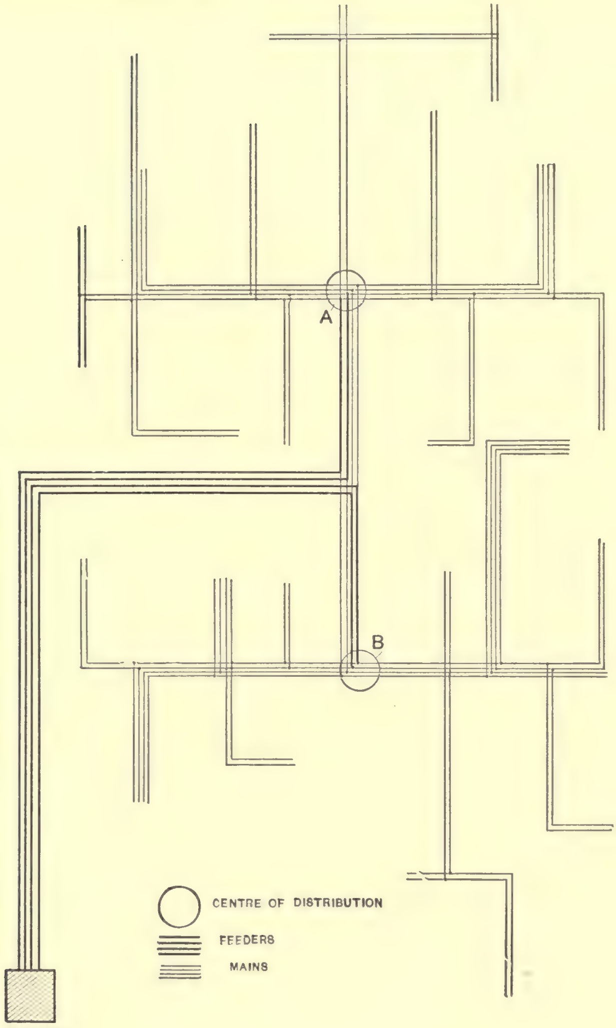


Fig. 7. Two-phase Four-wire Feeder.

100 amperes on each phase wire the neutral wire carries 141.4 amperes. If the same size of wire is used on each pole of the circuit, the energy loss is the same as it is in a four-

wire two-phase feeder under the same conditions. There being but three wires it is evident that only 75 per cent as much copper is required for the three-wire system as for a four-wire two-phase system under equivalent conditions.

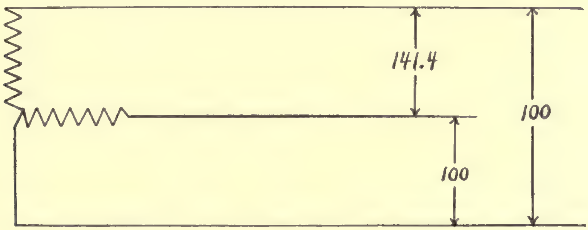


Fig. 8. Three-wire Two-phase System.

In cases where feeders are so short that they are loaded up to the current carrying capacity of the wires, it is desirable to use a larger conductor on the neutral. In such cases the saving in copper is not more than 10 to 15 per cent.

In the primary distributing mains where, for mechanical reasons, no wire smaller than No. 6 should be used, a saving of 25 per cent is generally realized.

With four-wire two-phase systems, it is usual to step up the voltage for any transmission of large amounts of energy by two transformers connected by the "Scott connection." (See Chapter VII.) This produces three-phase currents on the high voltage side, permitting the transmission to be made on the more economical three-phase system. The reverse arrangement is used at the remote end of the line when there is a light and power load to be distributed by two-phase currents.

Three-phase Systems. — Such systems are operated from generators having three sets of windings in their armatures, which are so placed that they deliver three equal voltage waves which are a third of a cycle apart. When these three wind-

ings are connected in series to form a closed ring the sum of the electromotive forces is always zero and no current flows in the ring.

When three wires are connected at the junctions between adjacent coils they constitute a three-wire three-phase circuit which is said to be delta connected. See Fig. 9 (*A*).

When the windings of the generator are so connected that the three corresponding terminals of the coils are joined to-

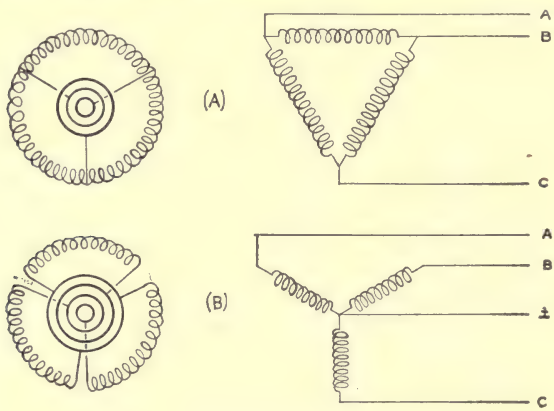


Fig. 9. Delta and Star Connections.

gether, as in Fig. 9 (*B*), the line wires are connected to the other three terminals and to the common or neutral point, making a four-wire circuit which is said to be Y or star connected. With a balanced load the fourth wire is not needed and a three-wire circuit may be used for motor loads even though it is supplied from a star connected source.

For general distribution purposes, the three-wire system is best adapted to use in the smaller cities where distances are not greater than can be properly covered at 2200 volts and where feeder loads are under about 500 k.w.

The four-wire system is normally operated at 2300 volts from phase wire to neutral with 4000 volts between phase

wires. This is more economical where the load is denser, feeder loads are heavier, and distances of transmission to outlying suburbs are greater, as is the case in the larger cities.

Three-wire distribution requires but three wires for the distributing mains while four wires are required in the four-wire system in places where power consumers requiring 25 horse power and upward are served. Three wires are sufficient in either system for power installations under 25 horse power as they can be served by two transformers in either case by the scheme of connections illustrated in Chapter VII. The cost of the extra conductor in the four-wire main system may largely offset the saving in feeder copper except where feeders are more than two miles long or where the load is so dense that the feeders are numerous and the mains do not extend over a very large area.

This applies chiefly to districts where there is so general use of power that all phases must be carried on the majority of the streets. In residence districts where the load is chiefly single-phase, it is usual to use two-wire mains, balancing them on the three phases as nearly as is practicable. In some cities this has been carried to the feeder system by putting all lighting on one phase and running on`y a smaller third wire for such three-phase wire service as may happen to fall within the area served by the lighting feeder. This makes the lighting feeder virtually single-phase, and has the advantage that pressure regulation may be made somewhat simpler as only one regulator is required.

Where lighting is carried on each phase with potential regulators in each wire, the regulation of the pressure on the different phases is somewhat complicated when the load changes more rapidly on one phase than on the others.

This may be seen by reference to Fig. 10 showing the phase relation of current and pressure in a three-wire three-phase circuit. The lines *AB*, *BC*, and *CA* represent the line pres-

sure. The lines *AR*, *BS*, and *CT* represent the resistance drop in the line wires with balanced load. *AU* and *CV* represent the drop in the *A* and *C* wires where the *CA* phase has twice as much load on it as the other two phases. The pressure

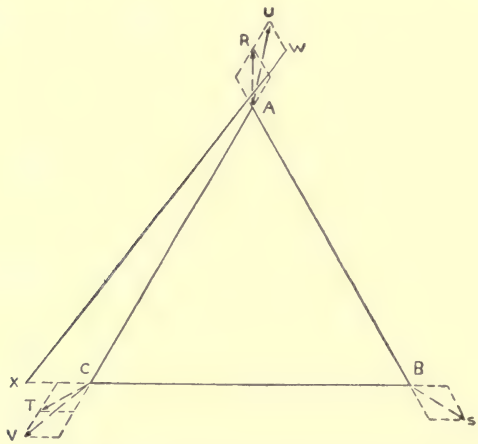


Fig. 10. Drop on Three-phase Circuit.

coil of the regulator in the *A* wire is connected across the *CA* phase, and it therefore adds pressure to the *C* phase along the line *AW*. The regulator in the *C* wire, drawing pressure from the *BC* phase, adds pressure along the line *CX*. Thus both of these regulators affect the pressure between the *C* and *A* wires. With a change in load which occurs on one phase, the regulators in both *C* and *A* wires must be operated to compensate for the additional drop in that phase. With hand regulation, close attention by the operator is required while the load is coming on in the evening. With automatic regulation and suitable compensating devices, however, this difficulty is not a serious one, and there are several cities of over 100,000 population in which the three-wire three-phase system is employed.

A typical arrangement of a three-wire three-phase feeder with single phase branches in a portion of the district served is shown in Fig. 11.

A desirable method of operating this system in residence sections is to carry all the lighting on one phase of a feeder with

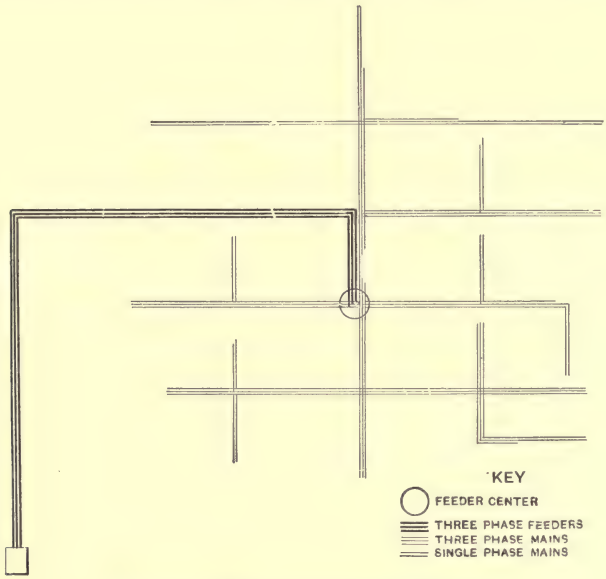


Fig. 11. Three-phase Three-wire Feeder.

a smaller third wire carried only to such points as require it for power users.

This plan permits the use of a single potential regulator on each lighting feeder, which permits of accurate regulation of pressure and reduces the disturbance due to power load to a minimum.

The *four-wire three-phase* system has several advantages over the three-wire system, and has been adopted in most of the larger American cities which have remodeled their early equipment or developed new systems since the year 1900. The first large four-wire system was adopted for the

outlying parts of Chicago in 1898, and that system is one of the largest of its kind in existence. A large suburban territory around Boston is served by the four-wire system, and it is in use in Cincinnati, Baltimore and some other smaller American cities.

The chief point of superiority in this system is that the transmission is effected at 3800 to 4000 volts, which increases the range of distribution to nearly twice that of the 2200-volt system. The pressure from either phase wire to neutral being 2200 volts, standard 2200-volt transformers are used for both light and power service.

The lighting branches are made single-phase as in other polyphase systems, but the importance of a careful balance of load on the feeder is reduced very greatly, as the neutral wire carries the unbalanced current and it is quite feasible to regulate pressure on all phases satisfactorily regardless of balance. In fact, one method of developing a four-wire feeder system consists in starting with a regulator on but one phase, all lighting being on that phase. As more lighting load is added another phase is equipped with a regulator and finally the third regulator is added. Such a method is quite satisfactory when a line-drop compensator is installed in the neutral wire, as well as in the phase wire.

When the area to be served is so large that it is not possible to distribute all the lighting load of a four-wire feeder from one point without too much drop in the No. 6 primary main, some of the principal mains may be made larger, or the territory may be so divided that all lighting in one district is on one phase and that in the other districts on other phases. Two of the heavy feeder conductors are then run to the center of the lighting district, thus shortening the mains and permitting each phase to be regulated for the drop on the feeder and mains on that phase. Such an arrangement of a four-wire feeder is shown in Fig. 12.

The neutral wire in this system naturally runs near earth potential and is therefore usually grounded at the generating station. This makes it necessary to look after the insulation of lightning-arrester cases, cables at points where they join overhead wires, fuse boxes and other fittings somewhat more carefully than in other systems. It is also necessary

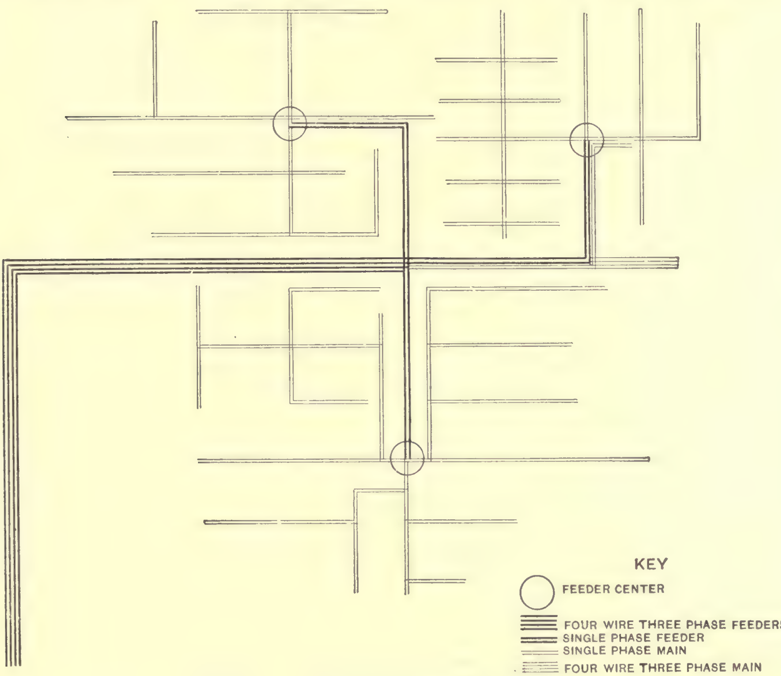


Fig. 12. Four-wire Three-phase Feeder.

to exercise more care in working on lines where there are two or more phases present, since the difference of potential between phases is about 3800 volts and that to ground is 2200 volts normally.

This system requires one-third the copper in the feeders which is required for a single- or two-phase system at 2200 volts, or 44.4 per cent of that required for a three-wire three-

phase system at 2200 volts under equivalent conditions. This saving is somewhat offset by the increased cost of four-wire mains as compared with two- or three-wire mains.

The smaller three-phase power users up to 25-horsepower may be supplied from two transformers with open delta-connected secondaries as in the three-wire system.

The supply of power service in manufacturing districts is sometimes accomplished by the use of separate power feeders, the lighting being carried on other circuits. The use of separate power circuits tends to produce a duplicate distributing system and requires increased feeder capacity on account of the lower power factor, while with combined service, the lighting tends to keep the power factor up. The diversity of demand between power and lighting loads also makes possible a considerable saving in feeder capacity where the lighting load in a given district is of the same order of magnitude as the power load.

Thus the policy of a combined feeder system is preferable from the standpoint of both feeder and main investment, in most cases.

With modern pressure regulating apparatus, there are not many situations where the lighting service cannot be made what it should be, when lighting and power is served from the same primary mains.

Arrangement of Primary Mains.—The primary main system cannot be interconnected as are the mains in a low-tension system, because it is impracticable to provide fuse protection which will isolate a section of main which is in trouble without simultaneously blowing other fuses through which the energy is supplied. Thus the primary system loses the advantage of parallel feeding, and the feeder end must be located as nearly as possible to the electrical center of the district which it serves, thus forming a center of distribution

with radial mains. These centers of distribution should be chosen so that the drop on the primary main will average about 2 per cent from feeder end to transformers. The limit is not always commercially feasible, however, in the case of lines to outlying districts.

In cases where a feeder follows a main thoroughfare along which most of the load is located, and the side branches are short, the "tree" system sometimes is used, as in Fig. 13. This tends to give high pressure at the near end and low pressure at the far end but saves the cost of a "back feed" main.

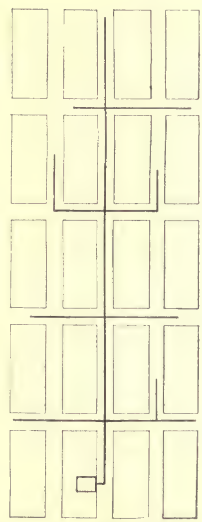


Fig. 13. Tree System.

The center of distribution plan of arranging primary mains is quite commonly used in the larger systems. In this plan the feeder is terminated at a point near the electrical center of the district which it serves, and branches are radiated in as many directions from this point as there are routes available, usually 3 to 4. In this manner the mains supplying service nearer the source are given the same pressure regulation as others which are served by the feeder under similar conditions of load and distance from the center.

By this plan the pressure may be regulated to maintain the correct value at the center of distribution at all loads and the range of pressure variation between no load and full load is a minimum. It is preferable, in most cases, not to use the tree system, since the pressure on the service near the source is higher than that farther away. The tree system is only suitable where the district served is so small that the drop at full load between the point where the first tap is taken off, to the end of the trunk is within permissible

limits, say 2 to 3 per cent. This condition is often found in serving business sections where load densities are high and distances therefore short.

In scattered residence sections during the development period and in suburban distribution there are groups of consumers whose demand is not sufficient to require a separate feeder. In such cases it is desirable to use two centers

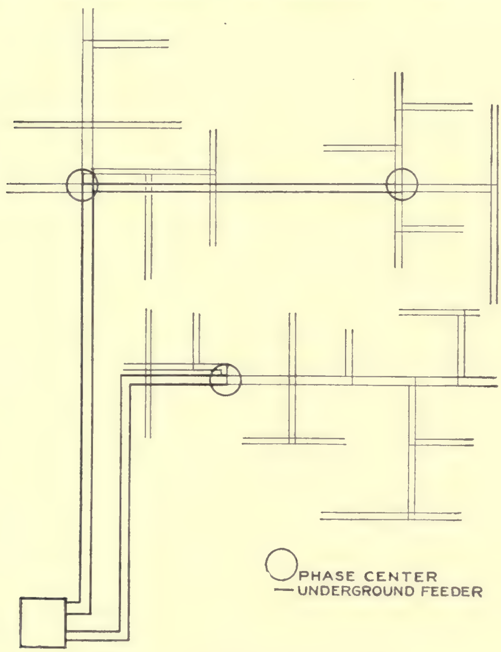


Fig. 14. Centers of Distribution.

of distribution or the scattered portion of the feeder may be treated as a tree system. These cases are shown in Fig. 14, one feeder having double centers of distribution and the other supplying all the load from one center, the mains being on the tree system.

In three-phase, four-wire systems a modified form of the center of distribution plan may be used, as shown in Fig. 12.

The center of distribution of each phase is located with reference to the electrical center of the single-phase load carried by that phase. Since each phase can be regulated for pressure separately, this gives a good distribution in scattered districts, and permits feeders to be loaded more heavily than is possible when the load is distributed from a single center. In the denser business districts it is possible to pick up enough load for a feeder within a small radius, and a single center is adequate.

The separate centers of distribution can be used in two-phase systems but do not work out well for three-wire, three-phase circuits, since the line drop compensators cannot be set to take care of drop in the single-phase branch after it leaves the other phases.

Emergency Switching Points. — One of the chief operating advantages of the center of distribution plan of arranging a feeder is that in an emergency, the principal mains having the center of distribution may be equipped with suitable disconnecting devices by which they may be cut off with a minimum of time spent in travel. With each principal main thus equipped, the repair man may readily determine which branch of the circuit is in trouble.

Where portions of the primary system are underground and where mains of adjacent feeders come together, it is important that there be suitable facilities by which the mains of the two circuits may be joined together in emergencies. Cable repairs require a considerable time and emergency connections must be provided in sufficient number to permit the minimum interruption of service. Emergency switching points are also necessary as a means of putting sections of cable out of service while new cable taps are being cut in. The safety of linemen and continuity of service largely depend upon the facility with which sections of the primary main system may be controlled.

An arrangement of two adjacent feeders with mixed underground and overhead lines provided with facilities for emergency switching appears in Fig. 15. This is arranged so that in case of the failure of any section of cable main, the service may be resumed as soon as the potheads on the cable poles connected to the main can be opened and the emergency connection between the overhead branches of the adjoining circuit closed.

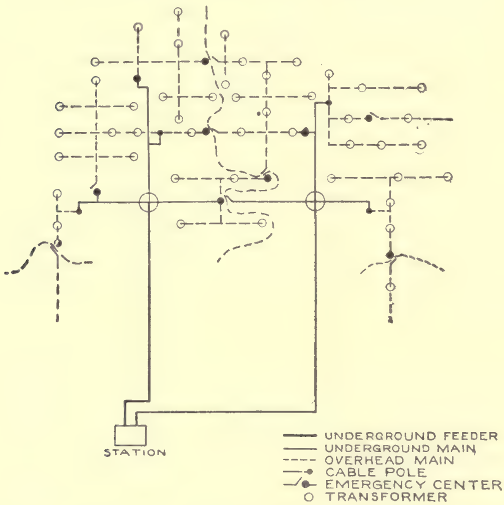


Fig. 15. Emergency Disconnectives.

Direct-current Systems.—Direct-current systems are two-wire at 550 volts, or three-wire at 110–220 or 220–440 volts. Two-wire, 550-volt power systems; which were established before polyphase systems were available, still survive in some American cities, partly because the general distribution is carried out by alternating current and partly because it would be a matter of much expense to abandon the system and exchange all the direct-current motors for others suited to the alternating-current system.

This voltage is high enough to permit economical distribution in medium-sized cities and the savings to be effected by a change are chiefly those incidental to the elimination of a separate set of lines paralleling the main lighting system.

Direct current at 220-440 volts on the three-wire system is distributed in a few medium-sized American cities. The saving in copper over a 110-220-volt, three-wire system hardly compensates for the loss in adaptability to high-efficiency lamps, fans, heating appliances and similar devices.

The three-wire system at 110-220 volts (approximate) is the one in most general use. The Edison systems established in the large American cities between 1882 and 1890 are for the most part still continued in the central portions of those cities, their growth having followed the development of the commercial and manufacturing interests very closely. In the larger cities the direct current is now derived chiefly from synchronous converters, the direct-current generating machinery having been replaced by more modern alternating-current units or held in reserve for use during the maximum-load period of the winter months.

The scattered mains originally laid have grown to heavy networks with feeders supplying them at frequent intervals and service connections into almost every building.

The direct-current system is maintained for the most important service because of the demand for variable-speed motors above referred to, and because of the availability of the storage battery as a reserve.

With storage batteries located at important points on the system, the interruption of service to a converter substation may occur with little or no interruption to the direct-current service. In case of a general interruption affecting several substations partial service may be maintained for a sufficient time to permit converters to be synchronized and gotten into operation again. There are several large direct-current networks in America which have not suffered a general shutdown during ten years or more.

The mains from which service is taken in the underground portions of direct-current networks are rarely smaller than

No. 0 or larger than 1,000,000 cm. In the heavily loaded districts 350,000 to 750,000 mains are commonly found. The feeders vary from 4/0 to 2,000,000 cm. The common sizes in the denser parts are 750,000 to 1,500,000 cm. The network is joined at street intersections through fused junction boxes. The main in each block, therefore, has a double feed, which enables it to carry a heavy load at any point more satisfactory than if there were no network arrangement. This also assists in maintaining continuous service, as the melting of a fuse at either end may merely drop the pressure without blowing the fuse at the other end. In case of a burnout of a main the fuses at both ends are usually blown, thus isolating the section and preventing the extension of the trouble to other blocks.

Combination of Systems. — A combination of alternating with direct current, or of two alternating systems, at different frequencies is usually found in the larger cities.

Direct-current systems are supplied by converting from alternating current, in many cases, and 60-cycle systems are supplied in part from a 25-cycle source of energy. When the generating system is operated at 60 cycles the direct-current service is derived through motor generators, as in the Boston and Philadelphia systems. Where 25-cycle energy is generated the direct-current supply is derived through synchronous converters. In recent years synchronous converters have been successfully introduced into 60-cycle system instead of motor-generators.

The superior economy of the synchronous converter as compared with the motor generator outweighs its lack of stability. Where the larger part of the load generated is distributed in the form of direct currents, as in cities like New York and Chicago, synchronous converters are therefore used in preference to motor generators.

The portion of the load which is distributed as alternating current in such cities must be generated by separate 60-cycle steam-driven generators or by 25-cycle motor-driven generators, since 25-cycle current is not well adapted to general lighting and power purposes and is not as salable as 60-cycle electricity.

When the load distributed at 60 cycles forms a considerable part of the whole, electricity is preferably generated at this

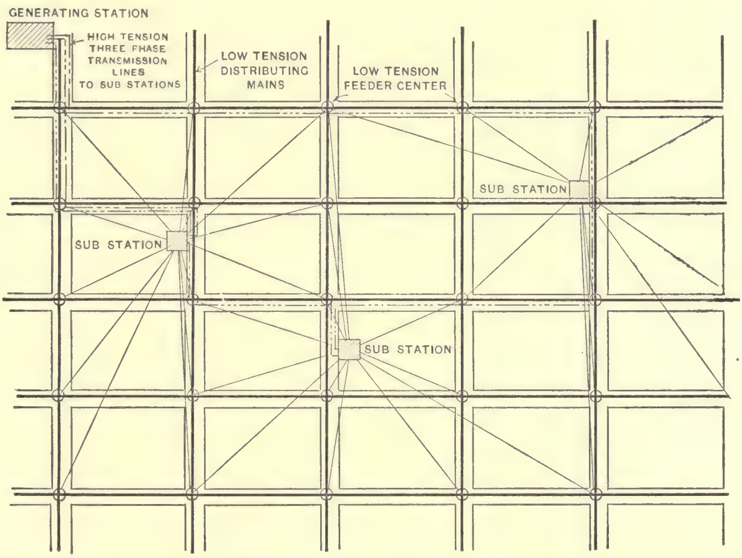


Fig. 16. Low Tension Network.

frequency and the portion required in the form of direct current is secured through motor generators. The selection of the transmission frequency is therefore usually governed by the relative amount of direct- and alternating-current load which is to be distributed. A typical arrangement of substations and direct-current network is illustrated in diagrammatic form in Fig. 16.

CHAPTER II.

TRANSMISSION SYSTEMS.

The transmission of energy in large quantities is necessitated by three general conditions: (*a*) the presence of water power at a point remote from the power market; (*b*) the presence of a group of distributing substations in a large center of population and (*c*) the existence of a group of towns and cities separated by distances greater than those separating city substations but yet within economical reach of a central point at which a power station may be located.

In the first case, the transmission line is the connecting link between the source of cheap power and the market where it may be consumed. The transmission is usually a through service without intermediate stations and involves very high voltages, steel tower lines, and a multitude of special problems which place its consideration beyond the scope of this treatise.

The second case, that of urban transmission cables connecting a group of substations in a densely populated district, is one common to all larger cities and will be considered in detail.

The third condition, that of district supply, is one which is being rapidly extended and is still in an evolutionary period.

These transmission systems connecting many towns and villages, in fact constitute a high tension distributing system with many problems peculiar to themselves.

All of these types of transmission lines are operated by three-phase currents at voltages and frequencies established by the conditions existing at various periods of development.

Voltage. — In general, the voltage selected for a transmission system should be such that energy can be delivered without excessive loss at the most remote parts of the territory supplied. The "rule of thumb" of 1000 volts per mile, which is often used as a guide, is based upon the fact that at this voltage, with copper conductors, a current density of one ampere per 1000 circular mils gives a loss of about 10 per cent. Thus the line carries approximately its rated safe current at a loss of 10 per cent. In the case of the very large cities where lines are called upon to carry 5000 to 10,000 kw. or more, to a single substation, this rule gives voltages which are too low for the most economical investment in cable. The adoption of 6600 volts in some of the large systems during the earlier years of development necessitated the use of excessively large cable sections in later years. Other systems which adopted 12,000, 13,200 and 20,000 volts later have been constructed much more economically because of the development of apparatus and cable which permitted the adoption of these higher pressures.

On the other hand, with district supply systems spreading over wide areas in which load densities are very light, the adoption of voltages less than 1000 volts per mile is sometimes possible. These lines are chiefly overhead and are operated at 20,000, 33,000 or 40,000 volts (nominal). At these pressures, cities and towns with loads of 50 to 500 kw. may be carried, at distances of 30 to 100 miles with reasonably satisfactory regulation and losses. As the load densities increase, the number of points of supply is apt to be increased, thus shortening the average distance of transmission as may be necessary.

The practical upper limit of voltage in urban systems is usually found in the manufacture of suitable underground cables. Various installations of cables operating at voltages up to 25,000 are in operation in America and there is an extensive suburban system operating at 30,000 volts in the vicinity

of the city of Berlin. In suburban and district supply systems, this limit is fixed by the inherent limitations of small transformer lightning arresters, fuses and other accessories.

Standard voltages should be selected for new installations, in order that advantage may be taken of machinery and apparatus already developed for these voltages, as far as possible.

Line Capacities.—A large proportion of the lines making up bulk supply systems in large cities are placed underground in lead-sheathed three-conductor cables drawn into ducts. The most economical use of capital is made when such cables are as large as can be properly handled. The kilowatt capacity of a high-tension cable at a given voltage increases more rapidly with increasing sizes of copper, than the cost of the cable. The most economical cost per kilowatt, therefore, requires the use of as large a cable as it is practicable to draw into a standard duct.

The following table gives the maximum sizes of three-core cable which are installed at the present time and the approximate continuous capacity of each at various voltages:

Volts.	Size of each core.	Amperes.	KV.-A.
6,600	350,000	290	3200
9,000	350,000	290	4500
13,200	300,000	245	5600
20,000	250,000	215	7100

The current values are taken for average conditions. They are somewhat high for situations where the facilities for heat radiation are poor, or where there is a considerable number of other cables liberating heat in the same duct line. These amounts of power could be exceeded for a few hours during a peak load, without risk of injury, in many cases.

The carrying capacity of overhead lines of the same size and at the same voltage is about 33 per cent greater than that of underground cables as given above. At 33,000 volts, the capacity of a line of 0000 A.W.G. wire is approximately 13,000 kv-a., or at 40,000 volts it is about 15,000 kv-a.

These loads are based on the carrying capacity of the conductor, and neglect distance. If the distance approaches or exceeds one mile per 1000 volts of line pressure, these capacities will give losses in excess of 10 per cent. They are therefore of interest for lines which are well within the distance at which drop in pressure is a factor, and as indicating what can be done in the way of loading lines in an emergency, where temporary overloading and excessive drop may be preferable to an interruption of a portion of the service.

Frequency. — In American practice two frequencies are standard for transmission purposes, namely, 25 and 60 cycles per second. Other frequencies, such as 30, 40, and 66 cycles, are in use to a limited extent, but are not considered standard. 25-cycle energy, however, cannot be used for arc lighting and is not satisfactory for incandescent lighting, except out of doors, owing to the noticeable flickering of the light. It is therefore necessary to convert the energy to 60 cycles for distributing purposes where 25-cycle energy is used in transmission. 60-cycle motors and transformers are less expensive than similar 25-cycle apparatus which further favors the use of the higher frequency for distribution purposes.

The use of a frequency below 45 cycles was necessary for many years in connection with direct current systems because of the unsatisfactory operation of synchronous converters at frequencies above 45. This was overcome with the development of interpole machines which made commutation on 60-cycle machines satisfactory and improved their reliability.

The choice of frequency was therefore fixed in most cities by the relative proportions of direct current and alternating current service. 25 cycles was chosen in cities like New York and Chicago where at the time the choice was made, the direct current service was over 80 per cent of the total service. In the first plant at Niagara Falls it was chosen at 25 cycles because of the use of large amounts of direct current energy for electrolytic work. This was the first large 25-cycle installation in America, and had great influence in making 25 cycles the standard for low frequency transmission in other systems.

The use of 125 and 133 cycles which was common in the early alternating-current systems was found too high for satisfactory pressure regulation with motor and arc lamp service, and 60 cycle systems were introduced at about the same time that 25 cycle transmission began to be introduced as an auxiliary method of distribution in direct current systems.

It was unfortunate for the users of frequency changers that the cycle 25-frequency was not made 30 cycles in order to simplify the design of the motor-generator set which had to be provided as a connecting link between the two systems.

These developments have led to the use of two generating frequencies in some of the larger American cities, which necessitates the use of frequency changer units (of 5000 kw. or larger in some cases) as a means of transferring load from one system to the other at certain times when operating conditions require it. Such a connecting link makes it possible to utilize reserve capacity in either system for the load of the other.

Reserve Lines. — In a system embodying a number of substations and perhaps more than one generating station, the arrangement of the transmission lines supplying substations,

with reference to continuity of service, becomes a matter of great importance. Important substations must have at least two sources of supply.

The supply of energy in bulk to points of conversion and distribution has been effected in American practice largely on the radial system; a radial being a line direct from the point of supply to the point of delivery.

The reserve supply is then secured by tapping a radial line or by extending a tie line from another substation as indicated in the typical cases shown in Fig. 17.

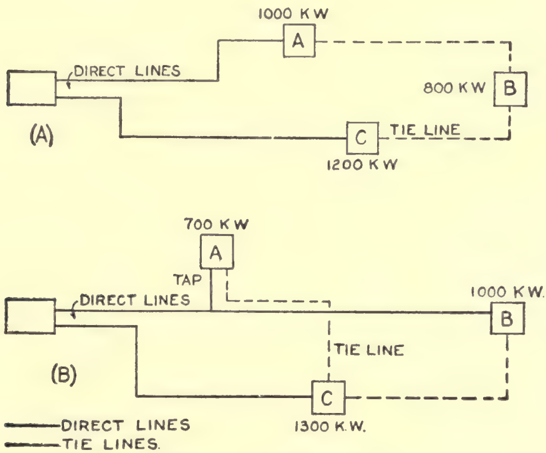


Fig. 17. Reserve Lines.

In Fig. 17 (A), the substation *B* can be carried either from a cable having a capacity of 3500 kw. acting as a radial line to substation *A* or from a similar line to *C*. If one radial is out of service, the entire 3000 kw. of *A*, *B* and *C* is carried by the other one.

After the load at *B* has become so large that the line to *A* or *C* is overloaded, if either of them fails, a radial is run to substation *B*, and this radial is then available as reserve for either of the others.

In Fig. 17 (B), the tap on the line to substation *B* is used as the normal supply for substation *A*. A tie line from substation *C* constitutes the reserve supply. As the load increases the tap is removed and becomes a part of a radial line to substation *A*. It is somewhat difficult to locate trouble on an underground cable when there are tap connections, and the number of taps should be limited to one if possible on this account.

The ring system of Fig. 17 (A) may be used to take in any number of industrial power consumers up to the capacity of

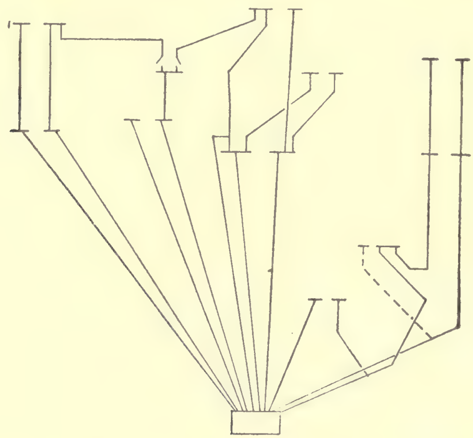


Fig. 18. Tandem Arrangement.

the cable; the substations in this case being on or very near the customer's premises.

The transmission system of one of the large companies in America has been developed on the principle of duplicate lines arranged with substations in tandem, as shown in Fig. 18. The converting units in each substation are divided into two sections so that an interruption on either line interferes with only one-half of the capacity in operation. These lines are protected by overload circuit breakers actuated by definite

time-limit relays so set that they will operate in tandem; that is, only that part of the service is interrupted which is beyond the fault in the cable.

As the loads increase and more radial lines are required, the importance of having a diversity of routes to guard against the failure of two or more cables to the same substation increases. This condition is illustrated in Fig. 19. The congestion near the power station must be guarded against by

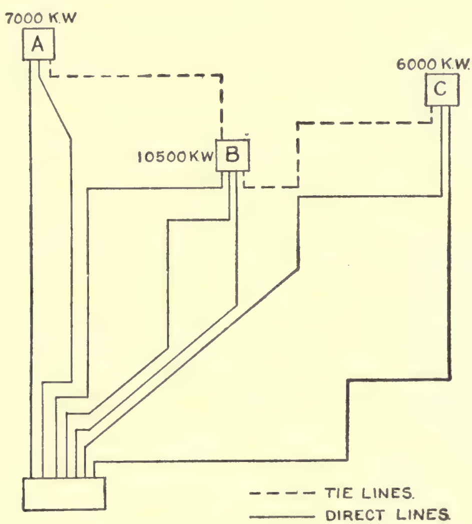


Fig. 19. Diversity of Routes.

limiting the size of duct runs and providing several conduit routes. The percentage of reserve investment becomes smaller, since one reserve line is sufficient for the three substations in this case. Thus the reserve investment is about one-eighth of the total in Fig. 19, whereas it is about forty per cent in Fig. 17.

The radial system is often arranged geographically through tie lines as if it were a network, but bulk supply systems

serving city substations have not been operated in parallel as networks, because of the lack of protective equipment which would adequately guard against unnecessarily extended interruption of service on lines which were not involved in trouble.

In England networks have been developed because of special protective equipment, the operation of which is based on pilot wires laid along with the transmission lines. The success of this system (see Merz-Price system, Chapter VIII) in maintaining continuous service to substations and wholesale consumers of 200 to 1000 kw. has been so marked as to engage the earnest attention of American engineers and designers in working out adaptations of it in America. The lack of pilot wires renders the immediate application of the Merz-Price system difficult, but other methods are being developed which operate sufficiently well to give rise to the belief that the parallel operation of high tension lines will become standard practice.

The perfection of such methods permits material savings in transmission line capacity since each group of lines must have independent reserve under radial operation, while with parallel operation the reserve capacity of all cables in the group is available. This may give sufficient capacity, often, to postpone additional line investment until a later date.

Prior to the development of the commutating pole converter, the largest unit which was considered practical had a continuous capacity of 2000 kw. These machines were designed to carry 2500 to 3000 kw., however, for about two hours. It therefore became common practice to install a line for each 2000-kw. converter or for two machines where 1000 kw.-units were installed. Thus the average load per cable was about 2000 kw. under normal operating conditions, but as the cables used had a capacity of 3000 to 4500 kw., there has been an accumulation of surplus cable capac-

ity in the larger systems, which could have been saved if means for parallel operation of cables and larger converting units had been available prior to 1910.

The introduction of converting units of 3000- to 4000-kw. capacity for direct-current work and three-phase transformers of almost any desired capacity for alternating-current distribution has done much to improve this condition in recent years.

Interurban Transmission Systems. — The extension of the lines of city systems to surrounding suburbs, and thence to other towns and cities within a radius of 50 to 100 miles or more has been the natural result of the development of the financial scheme under which a group of public utilities is assembled under one management through the medium of a holding company, or by consolidation.

The development of extensive distributing networks of transmission lines about such cities as Boston, New York, Detroit, Chicago, San Francisco and Los Angeles, has proceeded with great rapidity in recent years as a result of the modern financial policy of centralizing management, and unifying power supply systems.

The precedent established by the developments around the large cities has led to the application of this policy to smaller cities and towns where they are so located that they can be grouped together in one transmission system. In Illinois, these systems have centered about the coal fields. In the southern states several large systems have been built up in the cotton mill and iron working districts. In the western states the combination of mining and irrigation pumping have contributed largely to the development. In the eastern states such systems are based upon greater density of population and prevalence of general manufacturing enterprises.

Where the generating stations are located with reference to

a suitable supply of water for hydraulic operations, the stations are usually at some distance from the districts in which the power is consumed. In such cases the transmission is effected at voltages above 50,000, if the load is 10,000 kw. or more, and the line is used purely for transmission, without taps at intermediate points. These lines are constructed with high factors of safety which are justified by the importance of the service which they render. Steel towers or poles, suspension type insulators, long spans of heavy conductors and other engineering problems enter into their design, which are somewhat beyond the scope of this discussion and will not be considered in detail.

In some of the larger systems, the generating stations are so disposed, in the district served, that the lines above 50,000 volts serve as the bulk supply system to main distributing centers from which lines emanate at 11,000, 22,000 and 33,000 volts. These lines serve the large industrial users and the substations in towns and cities in the district, and in some places may parallel the higher voltage system along the same routes.

In other systems in more densely populated districts the main transmission system may be operated below 50,000 volts because of the shorter distances. In such cases the transmission tie lines may be used to serve large users along or within reach of the lines.

In this way lines operating above the ordinary distributing voltages are used as a high tension transmission and wholesale distribution system, and this type of service is rapidly growing in usefulness to communities which have before been without electric service and to those which have had partial service.

The design of transmission systems for this class of electrical distribution must be based upon the requirement that small towns and cities, isolated manufacturing establishments, and

other energy consuming enterprises, may be served at any point along the route of the line. The voltage must be high enough for economical operation and yet low enough to permit the use of transformers of any size from 15 or 20 kw. up.

Distribution within a radius of about 10 miles where the rural population and villages require electric service in amounts of 5 to 50 kw., may be served satisfactorily by the use of a double voltage four-wire three-phase circuit operating at 4600–8000 volts. Transformers are wound for 4600 volts and, except in wet weather, it is quite feasible to work on live lines safely while installing transformers. The use of this system permits voltage regulation to be maintained independently on the three phases from the main point of supply and entirely obviates the necessity of substations or regulating apparatus at any of the towns or villages served. Loads of 500 kw. to 1000 kw. or more may be served in this way very satisfactorily.

As distances are increased the voltages must be raised and there are systems operating at 6600, 13,200, 22,000 and 33,000 volts for this class of work. These systems are three-wire three-phase, some operating with neutral grounded and others without the earth connection. The neutral is grounded for the purpose of fixing the potential of the phase wires with reference to the earth and eliminating surges of high potential which are experienced on ungrounded systems when one phase becomes accidentally grounded. With a grounded neutral, a ground on a phase wire produces a short circuit which opens the circuit breaker, thus giving prompt indication of trouble and preventing any serious rise of potential.

The problems arising in connection with high tension distribution of this kind involve the questions of disconnective switches, out-door substations, fuses, lightning arresters and potential regulators which are not usually a part of a straight away transmission problem.

The use of disconnective switches is necessary at junction points where branches must be opened at times to facilitate location of trouble or to shift load from one point of supply to another. These are commonly open air switches mounted on poles and operated from a point below by means of levers, as shown in Fig. 20.

Where the loads carried are small as compared with the line capacity, or where the distances are short as compared with the voltage, as is the case in certain stages of development, the line drop is likely to be within 5 per cent and it is possible to serve the wholesale users on the line without potential regulators at the receiving substations.

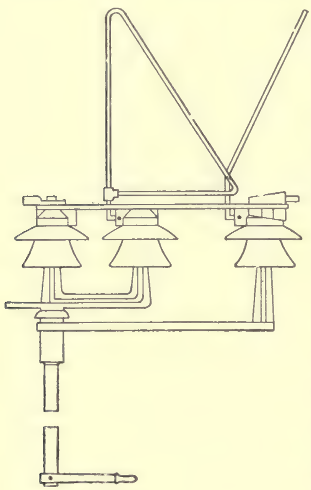


Fig. 20.

With the development of pole-type automatic regulators, however, it is becoming possible to provide pressure control for a town or industrial user without the expense of an attendant. This is quite important for certain classes of service which require better regulation than is afforded by the transmission line and station bus pressure control.

Where the town was large enough to have had a generating plant before it was taken over on the transmission system, a building is usually available and regulating equipment of the inside type is used. Where no building is available, all equipment is placed out of doors, since in many cases the cost of a building is not justified by the amount of income derived from the consumer and it is not necessary in any event, in many cases.

In the case of a factory, stone quarry, irrigation pumping plant or other industrial consumer, the equipment of transformers is mounted on poles or on a platform supported by poles, at a convenient point on or very near the consumers' premises. The equipment is usually provided with primary fuses, air break switches, and lightning arresters. In the case of a town, the transformers usually work from the transmission voltage to a voltage of 2200, the distributing line being operated in the usual way about town.

In towns having less than 20 kw. load which are compactly arranged, it is sometimes possible to use 110–220 volt distribution and so avoid the use of 2200 volt transformers. The main transformation is sometimes made at one side of the town, in order to avoid bringing the high voltage lines into the town. With this condition it is usually preferable to operate the distribution lines at 2200 volts.

The transformers must be protected from the effects of discharges of lightning in some manner in these substations. Where there is a building and an equipment of 150 kw. or more, the protection may be secured by the use of aluminum cell arresters of a type suited to the line voltage. This equipment is too expensive, however, for smaller installations and a multi-gap arrester equipment is often used. Even that is rather too expensive for the smaller substations on voltages of 20,000 or more. In these cases a plain horn gap arrester has been used to a considerable extent, the ground connection being provided with resistance sufficient to prevent an excessive flow of the line current to ground.

An out-of-door installation of this type is illustrated in Fig. 21.

The class of construction of lateral branches to towns or wholesale users from the transmission system, is determined partly by the importance of the load served and partly by the importance of the line from which the branch is served.

The cost of the extension should be kept within reasonable limits in view of the income to be derived and yet must not be of so low a grade as to jeopardize the continuity of service on the important main line.

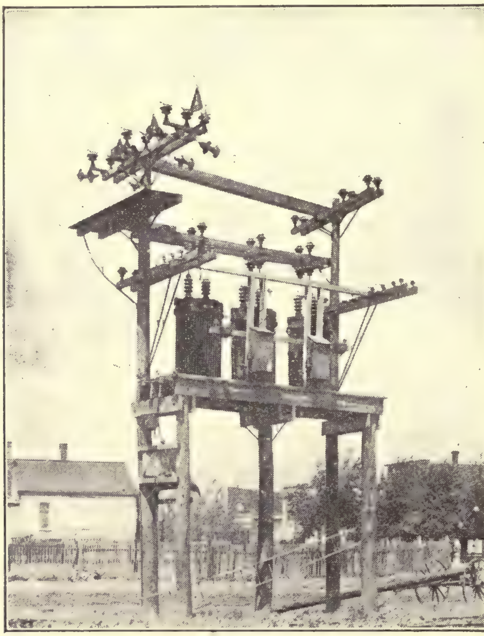


Fig. 21. Outdoor Substation.

In the case of small towns the loads are often less than 50 kw. and the 10 or 15 miles of line required may be constructed of iron wire on 25 or 30 foot poles in order to keep the investment per kw. within profitable limits. It is not unusual in running lines to growing communities to make an investment which is not profitable at first. As the community grows and overloads the line it is replaced by a better grade of construction.

CHAPTER III.

SUBSTATIONS.

In the development of a city distributing system, the radius of action from the point of supply tends to increase as the population grows. After a time the number of feeders to certain districts remote from the generating station becomes such that the transmission may be effected at higher voltage to much better advantage. Such transmission involves transforming and regulating apparatus at a point remote from the generating station, which in turn requires a building and other accessories, and the result is a substation. The substation involves an investment in real estate (or a rental charge), transforming apparatus, switchboard, etc., and an operating expense for attendance and repairs. On the other hand the feeders running into the district to be served by the substation occupy valuable duct or pole space and require a large investment in conductors.

Establishment of Substations. — It therefore becomes profitable to establish a substation when the amount required to pay fixed charges on the substation investment and its operating expenses is about equal to that required to meet the fixed charges and maintenance expense on the feeder equipments which would be required if a substation were not installed. In a growing system it may be advisable to anticipate this point somewhat and install the substation earlier, in order to avoid the loss due to the installation and removal of feeders which are transferred to the substation after but a few years' service.

The point at which the balance between substation cost and feeder cost is struck varies widely with different systems and classes of construction. In a low-tension direct-current underground system the number of substations must be greater than in an alternating system with 2200-volt mains, because of the shorter radius of action in low-tension systems.

There are also many local conditions to be considered, and two problems are rarely, if ever, identical. With a given class of construction, the radius of distribution and therefore the number of substations is fixed first by the voltage of distribution and second by the load density.

With a feeder loss of 10 per cent at maximum load and a current density of 1 ampere per 1000 c.m., the length of a feeder is approximately one mile per 1000 volts of working pressure. On this basis the radius of distribution at 220 volts is .22 mile or 1100 feet, and at 2200 volts it is 2.2 miles. There are usually some feeders which are longer than this on which the loss runs higher. When these become sufficiently numerous an additional substation becomes desirable.

It is sometimes necessary to establish a substation on account of a large block of load such as an amusement park, large retail store, manufacturing plant or other similar enterprise.

Classes of Substations. — Substations may be divided into two general classes according to the kind of electricity they are designed to distribute — viz., alternating current and direct current. Alternating-current substations are of two general types, transformer and frequency changer.

Direct-current substations are of three types, synchronous-converter, motor-generator and storage-battery.

General Principles. — The design of a substation building and equipment must be made with a view to economy of

operation, facility of repair and construction work, security of the service and employees, and a minimum first cost consistent with these conditions and with the importance of the service. Where growth is probable, due regard must be had for extensions of building or equipment, or both. The character of the building and equipment is fixed by the kind of service to be given, whether alternating- or direct-current, at high or low tension.

The economy of operation should be as high as possible, as the added expense of maintaining an attendant must be offset by the superior efficiency of the substation system as compared with feeders direct from a generating station.

The arrangement of apparatus with regard to the work of construction and repair men should be such as to minimize first cost and operation. Proper provision for repairs will shorten the time of a shutdown very materially, thus saving loss of income and injured reputation for reliability. No design is permissible which involves unusual risk of interruption to the service. The first cost must be kept within proper limits, since fixed charges on the investment form a considerable part of the cost of electricity supply and must be as low as possible.

Transformer Substations. — Transformer substations are used where the frequency of the distributing system is the same as that of the transmission lines, and only voltage transformation is necessary. Such a substation consists essentially of incoming transmission lines, oil switches, transformers, distributing switchboard, feeder regulators, switches, instruments, etc., and outgoing feeders. It will facilitate the discussion to consider a practical example of this class and the various elements which require treatment in the design.

Assume that a substation receiving energy at 60 cycles, 13,200 volts, is to deliver it at 2300–4000 volts on the four-

wire, three-phase system. The maximum load of 2400 kw. is to be delivered by four feeders. The building is to be located on a fifty-foot lot on a side street near the electrical center of the district which it is to supply. The value of the equipment and the importance of the service demand a fire-proof building. The external appearance will be suited to the character of the neighborhood. If it is in a manufactur-

Fig. 22. Transformer Substation.

ing district it may have the character of a factory building. If in a residence district it may be given the appearance of an apartment building. In suburban territory where land is plentiful, it is desirable to finish the building on all sides and surround it by lawn and flower gardens. Where it is desirable to combine the substation building with a district office, it is usual to locate it on a business street, placing the office building in front.

The interior of a transformer substation having air cooled transformers is illustrated in Fig. 22.

The arrangement of the interior of the building is necessarily restricted in many cases by local conditions which do not permit an ideal arrangement of the apparatus, but as such cases require special treatment, a building of ample size and proper shape to permit of an unrestricted design will be assumed available.

The arrangement of apparatus will, in general, be most desirable when it is such that the flow of energy progresses from entrance to exit in the most direct path possible. This makes the length of cables a minimum, tends to avoid crossovers, facilitates repairs and results in economical operation.

This is carried out in the arrangement illustrated in Fig. 23. It will be noted that the transmission lines enter at one side of the building, pass through their oil switches to a bus bar, thence through a smaller oil switch to the transformers. From the transformers the 2300–4000 volt energy passes through switches to the bus from which it is distributed. The outgoing feeders pass through switches and potential regulators and leave the building at the other side.

Two incoming lines are essential to continuous service. This necessitates a tie switch between them so that the whole load can be carried on either line.

Switches must be provided on each side of the transformers so that they can be isolated when necessary for repair and maintenance work.

The 2300–4000 volt bus is made double to permit repairs or alterations to be made without interrupting the service. It is also useful at times in permitting longer feeders to be carried at a higher bus pressure or from a different source of power.

The use of an auxiliary bus requires double-throw switches

throughout and adds to the first cost of the station. This may be omitted in small substations where there is a single incoming line and only two or three outgoing feeders.

The outgoing feeders leave the bus through single-pole

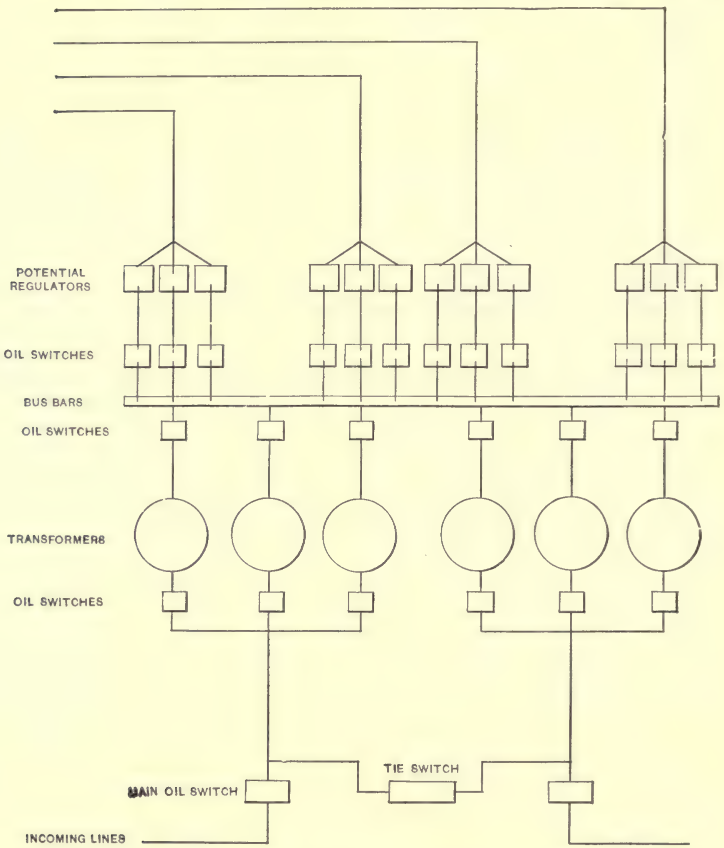


Fig. 23. Component Parts of Transformer Substation.

switches and pass through the regulators for the control of the pressure. With a three-wire three-phase system it is usual to employ three-pole switches, but in a four-wire, three-phase system each phase is independent and it is not desirable to

open the entire feeder when trouble occurs on one phase only, as is often the case.

In the arrangement suggested in Fig. 23, the high-tension switches occupy space next to the wall, with an aisle between them and the transformers of such width as to permit ready access for inspection, repairs or the replacement of a transformer. The 2300–4000 volt busses are at the rear of the control board, with an aisle between them and the regulators so that they may be accessible. The regulators are motor-operated and are placed near the wall in the path of the outgoing feeders. The control switches for the regulator motors are on the switchboard panels close to the voltmeter, so that the operator may control the pressure while watching the voltmeter. Less expensive hand-controlled regulators are sometimes installed where the arrangement is such that the handles can be extended to the front of the switchboard.

The high-voltage conductors between oil switches and busses are commonly insulated with varnished cambric and supported on suitable insulators. The lead sheaths of incoming lines and outgoing feeders are terminated in suitable pot heads, which serve to dissipate any static charge which may tend to accumulate and to exclude moisture from the insulation of the cable.

The arrangement suggested in this assumed case is of course an ideal one, since no limitation of space or other local conditions are imposed. In many cases the required floor space is not available or is too valuable for other purposes to justify its use for substation purposes. Under such circumstances, floor space may be economized by placing the potential regulators on a gallery above the switchboard, or the 2300 volt bus and switches in the basement. The latter arrangement brings them in line with the outgoing feeders, and is preferable if the basement is of suitable depth and size to give room to handle and install the apparatus. With a room which is not

long enough to permit the transformers to be set in a row it may be necessary to try various groupings of the oil switches and transformers until the best arrangement is found. Each proposed arrangement must be considered with reference to the disposition of the apparatus and connections in the basement as well as on the main floor. No design is justifiable which makes a nice-appearing installation of the main floor but which necessitates dangerous conditions elsewhere in the building.

Switching Apparatus. — The switches on the incoming line must be capable of opening the entire load under emergency conditions, and should therefore be of the oil break type with fireproof compartments for each pole. These switches must be equipped for protection from short circuit, which necessitates a set of current transformers on each line. Suitable space must be provided for these near the switch, as well as for the relays.

The switches are operated by alternating current with auxiliary hand control in the absence of any source of direct current for this purpose. The switches controlling the transformers may be of the tank type of oil switch, the transformers being arranged so that they can be disconnected entirely on both sides. The switches on the line side should be protected by overload relays, while those on the 2300-volt bus should be protected by reverse-energy relays to guard against the failure of a transformer coil.

These switches may be of the type which is closed against a spring by hand and opens automatically when tripped by the relay. The relays for primary and secondary of the transformers may conveniently be located on the switchboard panel which carries the secondary switch. The current transformers should be located in a place where they are convenient to the leads of the main transformers.

The switches on the outgoing four-wire feeders should be of the hand-closing, spring-actuated type of circuit breaker. Fuse protection is sometimes used on 2300-volt feeders, but it is not as satisfactory as circuit breakers, because of the longer time required to restore the service when a fuse blows, the greater likelihood of fuses blowing unnecessarily under heavy loads, and the difficulty of designing a fuse block which will not be injured by the operation of the fuse within a comparatively short time.

Outgoing feeder switches should have a capacity of 150 to 200 amperes at 2300 volts. It is not desirable to load distributing feeders any more heavily than this, and in scattered districts 100 amperes is as much as can be properly distributed from the feeder end.

Transformers. — The transformer equipment may be of the air-blast, oil-cooled or water-cooled type. Oil-insulated transformers are less subject to puncture by lightning or high-potential surges and are usually used with overhead lines for this reason. Air-blast transformers are the least expensive in first cost, but involve apparatus and ducts for the fresh-air supply. In a large substation this may become a serious difficulty owing to the space required for the air ducts. The circulation of water or oil permits more rapid cooling and is therefore desirable in the larger units in order to keep the size and first cost of the transformer within reasonable limits.

Where floor space is limited, air-cooled units are desirable, as they are smaller in external dimensions and are designed with a view to occupying a rectangular floor space of very small area.

With oil-cooled units of 500 kw. and upward it is advisable to provide drains to a sewer for the transformer oil so that in case it should become ignited it could be drained off to assist in extinguishing the fire.

With large high voltage transmission systems it is usual to install the transformers in separate compartments to guard against the spread of an arc or flames from burning oil to adjacent transformers. With units of 2000 kw. and larger this expense is usually justified in view of the importance of the service and the investment involved.

Reserve Capacity. — The selection of the size and number of units for a substation is a matter of great importance from both operating and investment standpoints.

The units should be as large as possible to insure low first cost per kilowatt and high efficiency, and numerous enough to leave sufficient working capacity in case a unit fails.

In the three-phase station used here for illustration, the use of two units on each phase would result in a reduction of 50 per cent in capacity on one phase if a unit fails. If the units are selected with a reserve capacity of 30 per cent, the load can be carried by running one unit at about 50 per cent overload until a spare unit is put in place of the defective one. Where the service is important a spare unit should be available at all times for emergencies. In a system with several substations, two or three sizes may be standardized, one of each being carried as reserve. Where there are several substations it is sometimes possible to secure reserve in part through tie lines from adjacent stations which may have spare capacity.

Switchboard. — The switchboard panels carrying control switches should be located in a position where the instruments may be readily observed by the operator, and at a sufficient distance from the wall to give reasonably good access for construction and repair work. It carries no high-tension connections except where the feeder switches are of the hand-operated type, in which case they are preferably mounted

on the panel with the instruments. Where remote control switches are employed, the switchboard carries only secondary low-pressure wiring, such as instrument connections, remote control circuits, compensator circuits and the like. Such a board must be located in a part of the room where it is accessible to the operator. The operation of remote control switches should be indicated to the operator by pilot lamps of red and green on the operating board.

Each feeder should be provided with an ammeter as a means of indication of the load carried and a voltmeter in connection with a line drop compensator to indicate the feeder end pressure to the operator. A power factor indicator is a desirable accessory on the main bus.

The transformer panels should be provided with ammeters and a bus voltmeter for each bus and phase. The control wiring for the transformer switches is also brought to the transformer panels.

The design of the switchboard should be carried out with a view to making as economical an arrangement of the apparatus as is consistent with safety of installation and operation.

The arrangement of the wiring for instruments, relays and similar apparatus should be carefully made with a view to making it secure from failure, accessible for testing and repair work, and neat in appearance. Where a number of wires are grouped on one or two panels, the use of terminal boards for testing and repair purposes is very desirable. These should be placed so that an instrument adjuster can get at them conveniently without disturbing the connections at the instrument terminals.

The switchboard should be of fireproof materials, marble or slate on angle iron frames being the most commonly used construction. The arrangement of switches and bus connections should be such as to minimize the danger of the spread of an arc. The location and arrangement should permit of

necessary extensions which may be required in connection with the addition of feeders from year to year.

Frequency Changer Substations. — The essential difference between the frequency changing substation and a transformer substation lies in the presence of motor generators. The incoming lines with their high-tension switching equipment and outgoing feeders with their switchboard and regulators are practically identical under equivalent conditions of load and space available in the two kinds of substations.

The motor generator outfit requires about the same floor space as an equal capacity in single-phase transformers when the motor is wound for the transmission voltage and the two machines are mounted on a common bedplate with a short shaft and two bearings. When designed in the vertical form there is some saving in floor space in the larger units.

Where the transmission is at a pressure too high for the motor windings direct, the motor generators require transformers and this increases the required floor space of the substation very materially.

With a substation of 2500 kw. capacity with synchronous motor generators taking energy at the line voltage the units should consist of two 1000-kw. and one 500-kw. and the arrangement might be made similar to that shown in Fig. 24.

It will be noted that this substation includes exciters for the fields of the motor generators and a high-tension starting bus fed by a reactance coil, for use in bringing the synchronous motors up to speed, at reduced pressure. A single reactance coil is provided together with double-throw switches on the motors so that any motor can be thrown to the starting bus and started from the one starting coil, the cost of the bus and double-throw switches being less than that of extra reactance coils. Duplicate exciters driven by separate motors at the transmission frequency should be provided, as they must be

started at times when the station is shut down, and reserve capacity must be available in case repairs become necessary on either unit. In some cases it is sufficient to have two

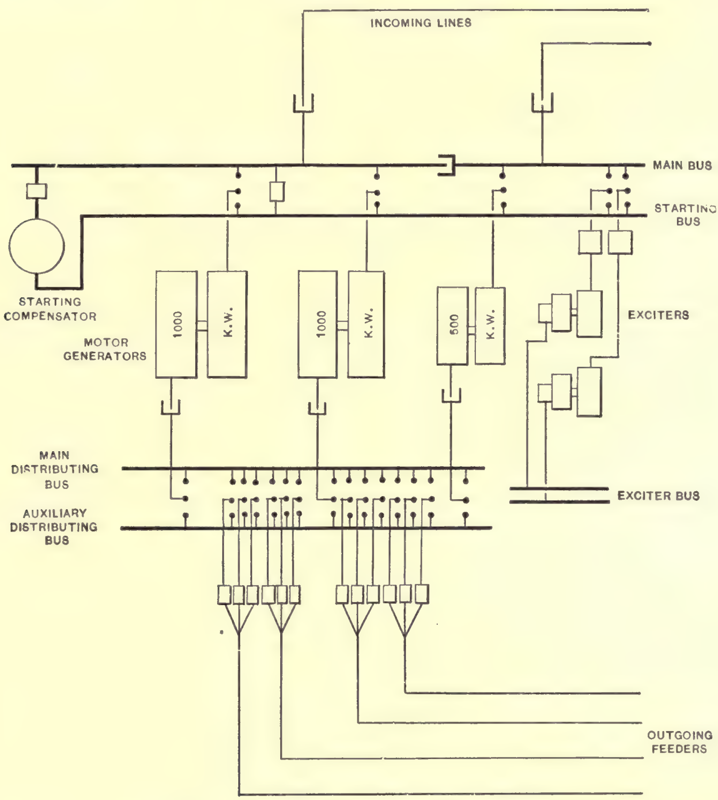


Fig. 24. Frequency Changer Substation.

exciter units separately driven, the others being driven by connection to the main units.

Where the presence of direct current is taken advantage of for automobile charging, traveling crane or hoist service, it is important that the direct current bus be divided so that the fluctuations of load will not affect the generator fields and

so produce pressure variations throughout the entire system. Where Tirrill regulators are used, it is desirable to have them control the pressure on the 60-cycle generators only. This necessitates the use of a separate direct current bus for the synchronous motor excitation.

The exciter units being less than 100 kw., it is usually not practicable to use motors wound for the line voltage to drive them. This requires a set of transformers and permits the use of low-voltage induction motors which are less sensitive to shocks on the transmission system. The entire control of the exciter may thus be placed on a low-voltage switchboard.

One of the chief points of interest about such a substation is the method of starting and synchronizing the motor generator sets. When a unit is to be put in service it is connected to a starting bus supplied by an autotransformer at 40 per cent of the transmission line pressure. The switches controlling the direct current for the fields of the motor are left open. The oil switch controlling the motor is then closed to the starting bus and the unit begins to revolve as a hysteresis and induction motor. When the unit is at approximately synchronous speed the field is excited, thus drawing the unit into step as a synchronous motor. This usually causes a rush of current for a very brief interval of time, as the machine is likely to be out of phase at the instant the fields are excited.

When the conversion is from 25 to 60 cycles this usually does not complete the operation of synchronizing, as the 60-cycle generator is not necessarily in phase with its bus when the 25-cycle motor has been synchronized. The ratio of the number of field poles on the 25-cycle motor to those on the 60-cycle generator must be as 25 is to 60 or as 10 is to 24. When a 10-pole field is mounted on the same shaft with a 24-pole field, as is usually the case in a 25–60 cycle frequency changer, only one set of poles on each field can be lined up in

the same radial plane. In Fig. 25, the poles which are aligned in the same radial plane are represented by the heavy diameters. When the 25-cycle machines are synchronized, any of the five sets of poles on the incoming machine may fall into

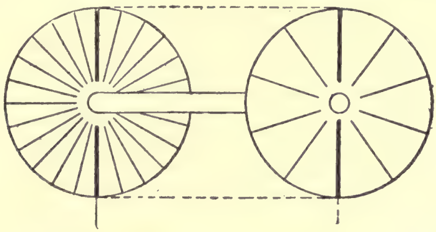


Fig. 25. Poles of Frequency Changer.

step with the poles represented by the heavy line on the operating unit. When the 25-cycle machine has fallen into step, as in Fig. 26, on the pair of poles next to the one represented by the heavy line in Fig. 25, the incoming 60-cycle

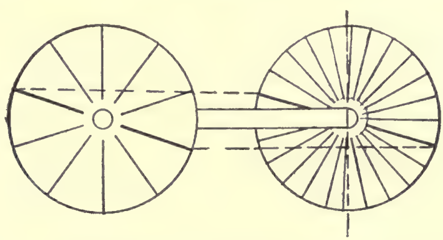


Fig. 26. Displacement of Phase, Frequency Changer.

machine is held out of phase with the operating unit as shown by the dotted vertical line. If the rotation is counterclockwise, the machines can be brought into phase by cutting off the supply of energy from the incoming machine and allowing it to slip back one pair of poles, at a time, until the heavy lines are in phase with each other. The machines are then in phase on both 25- and 60-cycle ends. A special synchroscope is employed which has five points corresponding to the

five positions in which it is possible to bring the 60-cycle machines into synchronism. The dial is shown in Fig. 27.

In synchronizing if the 60-cycle pointer takes position No. 4, it is necessary to "slip poles" four times before the 60-cycle machines can be thrown in parallel.

Fig. 27.

These complications do not arise in synchronizing a single frequency changer with a 60-cycle generator driven by a prime mover, as the prime mover can be adjusted to bring it into phase.

A typical substation of this class is illustrated in Fig. 28. The exciter for the vertical unit is mounted at the top, the

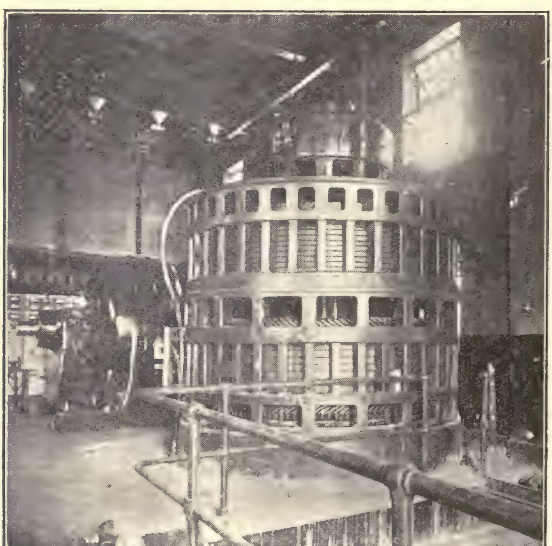


Fig. 28. Frequency Changer Substation.

armature being carried on the main shaft. In this substation the exciter for the 2000-kw. unit is provided with suitable switching arrangements which permit its use as a direct-

current motor in bringing the unit up to speed. This relieves the transmission system of the shock of starting as an induction motor. Direct current is supplied from one of the other exciter units for this purpose. The vertical unit is carried on a special roller step-bearing. Several of these 2000-kw. units are in service in the city of Chicago, in substations where the saving in floor space, improved efficiency and slightly lower first cost made their adoption desirable.

Direct-current Substations. — The direct-current substation receives high-tension alternating current energy and converts it to low-tension continuous current energy, for distribution. The battery substation receives continuous low-tension energy and delivers the same, the function of the battery being to store energy for use in an emergency.

Converting direct-current substations utilize motor generators or synchronous converters. In systems generating energy at 25 cycles, the synchronous converter is employed very generally because of its greater efficiency and lower cost as compared with motor generators. Where the generating system produces 60-cycle energy the synchronous converter was not employed until recent years because of its lack of stability, but the direct-current supply was derived from motor generators. Both synchronous and induction motor generators are employed. The synchronous motor generator is very desirable because of the ability to control the power factor thus offsetting the effect of inductive loads elsewhere in the system. It is, however, subject to the disadvantage that it is thrown out of step rather easily by disturbances in the transmission system. Thus a short circuit at some remote point may at times cause the synchronous motor to fall out of step and shut down unnecessarily.

The induction motor having no power-factor control is at a disadvantage in that respect, but it is not so easily thrown

out of phase sufficiently to cause it to be shut down and therefore has much more stability than the synchronous motor. The efficiency of the synchronous motor is somewhat better than that of the induction motor.

It has therefore been usual in the larger 60-cycle distributing systems, to equip direct-current substations with both synchronous and induction motors. This permits control of the power factor and yet retains the necessary degree of stability in a part of the equipment during an emergency.

In recent years the development of interpole converters has eliminated the more serious faults of 60-cycle machines and they have been used instead of motor generators.

Efficiency of Converting Machinery. — The comparative efficiencies and costs of a few principal sizes of motor generator and synchronous converter sets, as presented by Allen in a paper before the Association of Edison Illuminating Companies in 1908, is presented in Table I.

A study of this table shows that all sizes of 25-cycle motor generators have efficiencies about 4 per cent less than those of synchronous converters of equal capacity. The 25-cycle induction motor sets are slightly more efficient than the synchronous motor sets. The synchronous converter costs less in all sizes than the motor generator. At 60 cycles the synchronous motor sets are slightly more efficient than those driven by induction motors, while the converter is about 3 per cent more efficient than either.

The cost is nearly the same per kilowatt for motor generators as for converters at 60 cycles. These figures apply to converters and motor generators having interpoles. The converter costs include air-blast transformers.

Low-tension Switchboards. — The direct-current distributing equipment being operated at low potential is radically

TABLE I. — EFFICIENCIES.

K.W.	Per cent load.	25 Cycles.			60 Cycles.		
		Syn. mot. gen.	Ind. mot. gen.	Syn. converter.	Syn. mot. gen.	Ind. mot. gen.	Syn. converter.
		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
300	100	84	85.3	89.5	86.7	84.8	88
300	75	82.3	83.3	88.5	85	82.3	86.7
300	50	77	79.8	86.5	81.7	79	82.5
500	100	85.5	86.8	90.8	87.8	86.3	89
500	75	83.7	84.8	90.3	86	84.3	87
500	50	79.5	82	88.3	83	81	83
1000	100	87.5	87	91.8	87.8	87	....
1000	75	86	85.8	90.5	86	85.3	....
1000	50	82.2	82.3	90	83	82	....
APPROXIMATE COST PER KILOWATT.							
300	......	$26.20	$26.35	$25.15	$25.75	$25.85	$25
500	......	24.70	24.35	22	23.2	23.40	22.7
1000	......	20.25	19.85	19.80	19.45	19.50	....
FLOOR SPACE, SQUARE FEET.							
300	......	80	80	91	67	67	96
500	......	122	122	131	110	110	150
1000	......	136	136	170	140	140	....

different from the 2200-volt alternating-current equipment before described. The bus bars are of bare copper about half an inch thick and from three to six inches wide, built up, with air spaces between for radiation, to the required number to carry the current. These are mounted at the back of the switchboard so that the connections to the generator and feeder switches may be as short as possible. The chief consideration in the design of such boards is an arrangement using a minimum length of copper, as it is necessarily of heavy cross-section. The board should, therefore, be as short as possible, but the opposite polarities should not be so close as to endanger the service in case a short circuit is made.

The arrangement shown in Fig. 29 and Fig. 30 accomplishes these objects very effectively. The upper row of switches are all of one polarity and the lower of another. The neutral

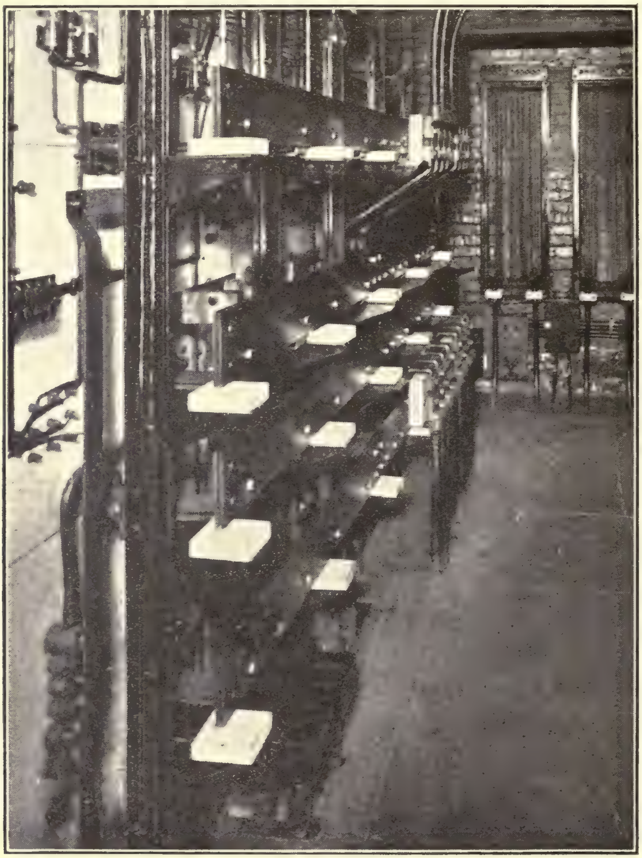


Fig. 29. Rear of Low Tension Switchboard.

conductor need not be switched and is connected direct to the neutral bus. The separation is ample and the length of bus-bar copper per feeder is about 6 inches for each pole of the bus.

This close spacing necessitates the use of the edgewise type of ammeter, an instrument being placed on each side of the three-wire feeder. The location of the polarities is usually standardized for the sake of uniformity. That is, the

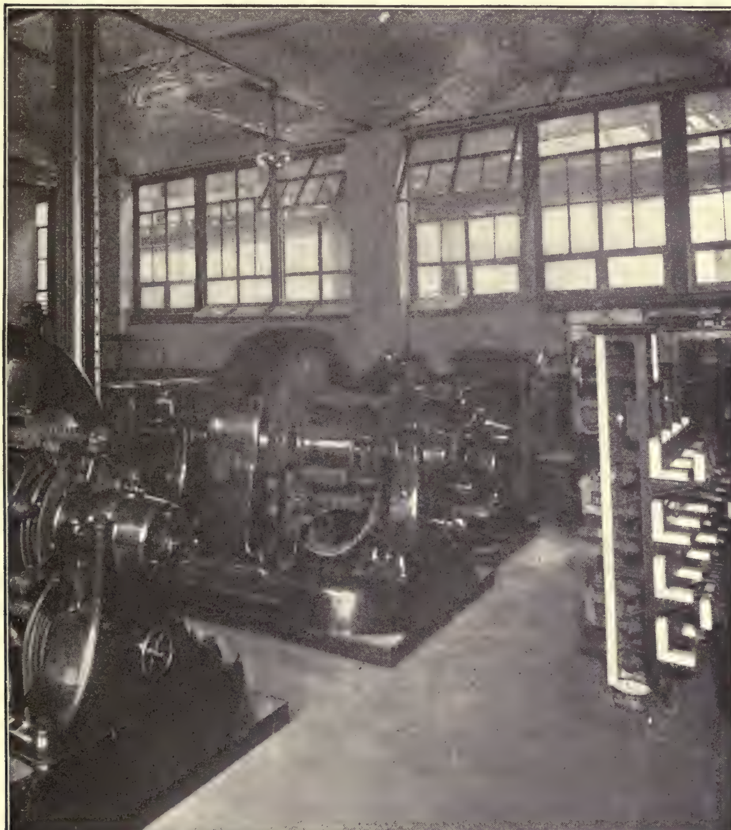


Fig. 30. Synchronous Converter Substation.

positive bus is placed above or at the right, and the negative below or at the left, or *vice versa*. Separate voltmeters are not necessary for each feeder in direct-current networks, but the pressure wires brought from the feeder ends are terminated

in a multiple-point switch so arranged that the pressures on the feeders may be read on a single voltmeter successively. The bus pressure is usually indicated by a separate voltmeter, as this pressure should be visible to the operator at all times.

The individual regulation of feeder pressure is not necessary in direct-current systems except for very long feeders which may be equipped with a booster set, or with very short feeders which may have a resistance in series to absorb part of the pressure.

Booster sets for use on three-wire feeders commonly consist of two generators of sufficient ampere capacity to carry the full load of the feeder and voltage range sufficient to make up for the feeder loss, usually at least 40 to 50 volts. These are driven by direct connection to a 230-volt motor of proper capacity. The booster generator fields must be designed to operate throughout the full range of pressure without trouble at the brushes, and must have independent field-rheostat control in order to permit compensation for drop on the neutral in case of unbalanced load. The location of a booster set should be such that the length of the feeder cables which are looped through the booster will be as short as circumstances will permit.

Feeder resistances are to be avoided as far as possible, and are usually not necessary on more than one or two very short feeders. Where necessary, they must be of a design which will carry the feeder current at full load without excessive temperature rise. This necessitates a special design of rheostat. Wire coils have been used for smaller feeders, but for those carrying 500 amperes and upward, strips of heavy, galvanized sheet-iron, mounted on suitable insulating supports and surrounded with a wire netting for protection, have given good results. There should be several sections so that the operator can adjust the resistance for different loads.

Motor-Generator Substations. — Motor generator converting sets for substations are commonly installed in sizes of 300 to 1000 kw. In these sizes the motors are preferably wound for the transmission voltage where pressures less than 15,000 volts are used, as the extra cost and space required for the transformers is a considerable item. Direct current is delivered to the distributing bus by the generator.

Synchronous motor sets are started preferably from the direct-current side in order to avoid disturbance in the transmission system, due to large starting currents. They are then synchronized and connected in parallel with the transmission system. Induction motor sets are started by the use of resistance in the rotor circuits which gives good starting torque with a starting current little in excess of full-load current. The induction sets are started first in an emergency, thus furnishing direct current from which to start the synchronous sets. The high-tension line equipment is similar to that outlined for a transformer substation. Control of the direct-current pressure is had by means of the field rheostats of the generators.

Synchronous Converter Substations. — In converter substations the electricity received from the transmission system passes through suitable oil-switching arrangements to step-down transformers which deliver a secondary pressure suitable for the rotary converter. From the transformers the current passes through a potential regulator to the collector rings of the converter and thence through its windings to the commutator from which direct current is delivered to the brushes. The direct current passes through a circuit breaker and switch to its bus bar, from which the feeders are carried to the distributing mains. Two or more direct-current bus bars are usually provided to facilitate the regulation of pressure during the period of heavy load.

The three-phase shell type of transformer, air cooled, has been used quite generally for this class of service owing to the economy in first cost and in floor space. The air for cooling is blown through ducts within the case, and in substations of 2000 kw. or more it is sometimes necessary to provide ducts to carry the heated air outside the building. This requires a suitable blowing outfit and space for air chambers under the transformers.

Types of Converters. — Synchronous converters are provided with shunt or compound field circuits. They may also have interpole windings and a synchronous booster for pressure control.

Shunt machines were formerly used for lighting work exclusively. With the shunt machine it is necessary to use a regulator for control of the direct-current pressure, since the variation of the shunt field strength changes both power factor and pressure, and the use of the shunt field to control pressure produces undesirable power factor under certain conditions of load and pressure on the incoming line.

The adaptation of the interpole field to synchronous converters greatly improved conditions of commutation and permitted the development of larger sizes of 25-cycle converters than had previously been permissible. The maximum size available prior to 1910 was 2000 kw., while converters of twice this size were put into service within a few years after the introduction of the first machines of the interpole type.

A modification of the interpole machine known as the split-pole converter was developed, but has not been generally employed. The split-pole machine has three sets of field windings with separate rheostat control, the purpose of which is to secure variation in pressure by changing the form of the voltage wave without affecting the power factor seriously.

The manipulation of the fields is rather complicated and the machine is somewhat larger than other types of converters.

The space required for the induction regulator and its connections, and its liability to injury when subjected to the mechanical shock of a short circuit, suggested the desirability of the use of the synchronous booster type of converter with interpoles to assist in commutation.

This machine carries an alternator on the main shaft with its windings in series with those of the converter armature, as shown in Fig. 31.

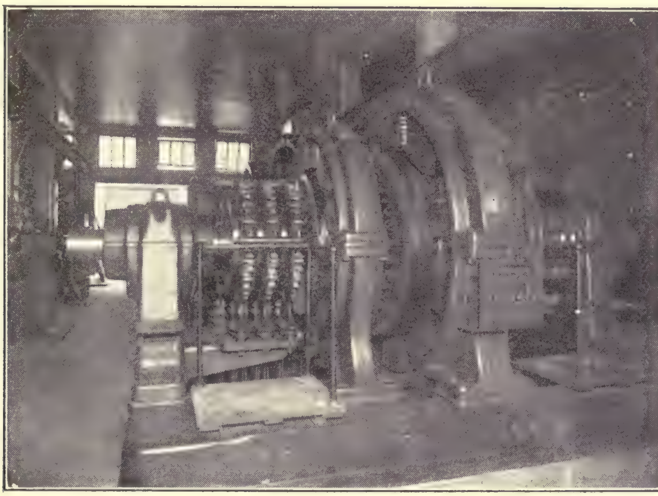


Fig. 31. Booster Type Converter.

The booster is wound to give a range of about 10 per cent of the rated pressure of the machine. Its field is reversible and this gives a range of 20 per cent in the pressure delivered to the direct-current bus bar. This range can be more readily increased to meet an emergency than is possible where an induction regulator is employed.

The advantages of simplicity of connections and greater

flexibility are such that this type of converter has been generally adopted in recent years.

In substations having units of 500 kw. or larger it is desirable to use converters wound for the voltage across the outer wires, in order to avoid the multiplication of the number of units, and the increased expense incident thereto. The unbalance of the system may be cared for by one pair of 110-volt machines or by a motor-generator balancer set or by the use of six-phase diametrically connected transformer secondaries arranged as in Fig. 32. The latter plan has the advantage that no 110-volt machines are required in the substation. The neutral of the direct-current system is connected directly to the secondary neutral of the transformers and any unbalance is thus cared for. The unbalance in a large system is rarely over 5 per cent and the scheme is found very satisfactory in most instances.

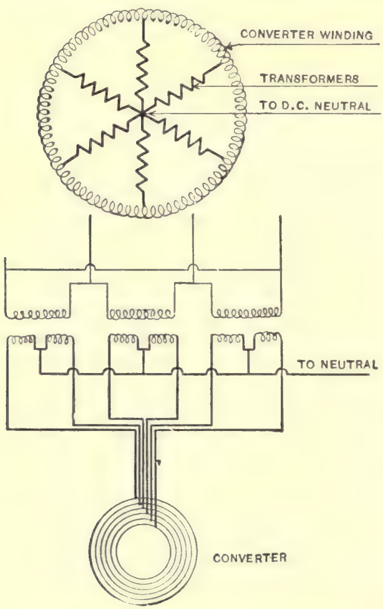


Fig. 32. Connections of Six-phase Converter.

The use of the six-phase connection and converter winding reduces the length of the path traveled by the current in passing through the armature and thus reduces the losses and the heating. Theoretical calculations based on sine waves indicate that a direct-current generator rated at 100 kw. may be rated at 131 kw. as a three-phase converter, or at 194 kw. as a six-phase converter, or the same rise of temperature.

The theoretical ratio of transformation in voltage in passing from the collector rings on the alternating-current side to the direct-current brushes is as 61 to 100 in a three-phase converter and as 71 to 100 in a six-phase converter. These ratios are based on the assumption of a sine wave of E.M.F. and may vary somewhat in actual practice.

It is usual to protect the converter by a reverse-current relay which opens the circuit breaker in case the flow of energy is reversed, and shuts the machine down. Without such protection the reverse current may weaken the field of the converter and cause it to accelerate quickly to a dangerous speed. The reverse-current relay does not operate below 10 per cent of full load, and a speed limit consisting of a centrifugal switch is often provided as further insurance against dangerous peripheral speeds. The speed limit is rarely called upon to act and should, therefore, be tested at regular intervals. Accidents to converters in which machines have been wrecked have occurred in nearly all large systems, and the provision of such accessories must not be overlooked where the unit operates in parallel with a direct-current system having other sources of supply.

Starting of Converters. — The arrangement of starting devices for synchronous converters is a matter of great importance, as it must be possible to start them quickly and without serious disturbance to the system in regular operation and in emergency. The converter may be started by a supply of current from either side or by a starting motor direct connected to the shaft. When started from the direct-current side a rheostat is used in series with the armature, as in starting a direct-current motor. The starting current, however, has two paths, one through the converter windings from brush to brush, and another through the collector rings to the transformer coils and thence back again to the con-

verter armature. While the converter is turning slowly, the frequency of reversal of the current through the transformer coils is low and the choking effect is small. The starting current from the direct-current side is, therefore, more than that of a motor of the same size without load. When the machine has come up to speed the potential regulator is adjusted to bring the pressure of the converter up to that of the transmission system, and the rotary is synchronized with the transmission system and connected to it. The field and regulator are manipulated to bring the power factor up to unity and to adjust the load carried by the unit to the desired amount.

In case a total shutdown of the system removes the supply of direct current for starting, means must be at hand for starting from the alternating current supply. Converters may be started from the alternating side with the field coils open as in starting a synchronous motor, and the pressure reduced to about half normal pressure to keep the starting current within limits. This may be done by means of a starting compensator on the high-tension side of the transformer or by means of taps on the secondary winding. The latter is preferable as no autotransformer or extra high-tension switching operations are required.

In this method after the machine is brought up to speed its fields are excited and the polarity noted, as it may come up reversed. If so, the direct-current voltmeter on the machine gives a negative reading. The field connections are then reversed by means of a switch provided for the purpose and the machine slips back one pole. As soon as it has done so the direct-current voltmeter swings to a positive reading, when the field is again reversed and the polarity remains correct. The starting switch is then thrown to the full pressure, the machine pressure is equalized and it is connected to the direct-current bus.

The current required in starting from the alternating-current side is from 150 per cent to 200 per cent of full-load current on a 500 kw. converter and somewhat less on larger sizes. The direct-current starting current, however, is but 25 to 30 per cent of full-load current. This small starting current makes this method preferable in cases where there are several machines or where the direct-current distributing system has sufficient capacity to furnish the starting current without serious disturbance. In such cases the normal method of starting is from the direct-current end.

Sufficient machines should be equipped for alternating-current starting in a given substation to insure a supply of direct current for starting the other units. Where sufficient storage battery capacity is installed the direct-current supply may be relied upon at all times.

The synchronous converter has also been adapted to operation on a vertical shaft in a manner similar to the frequency changer described heretofore. This machine is, however, supported on a bearing which operates on a pedestal that passes up through the center of the machine to the top. The bearing is thus accessible from the top by the removal of a plate instead of from below. The general arrangement is illustrated in cross-section in Fig. 33.

These machines have been made in units of 1000 and 2000 kw., the first of this type having been installed in Chicago in 1907.

The interior of a converter substation is illustrated in Fig. 30.

Storage Battery Stations. — One of the principal advantages of the direct-current system of distribution is the possibility of the use of a storage battery reserve. Before the use of the battery became general, it was not an uncommon thing in the larger systems to have the service seriously interrupted through accident in the generating or transmission

system. With the introduction of the storage battery these interruptions were largely obviated, only serious accidents affecting the major part of the system being the cause of shutdowns. The smaller disturbances in a large system pro-

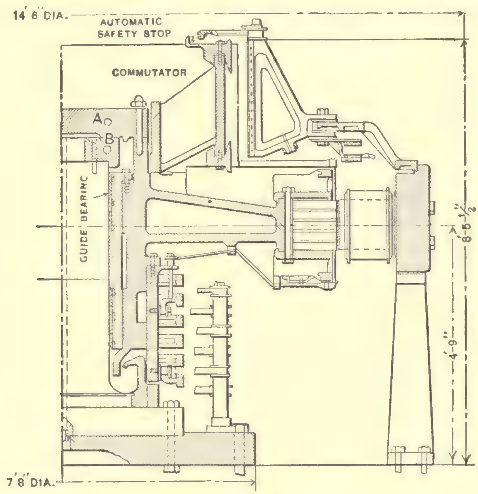


Fig. 33. Section of Vertical Converter.

tected by batteries do not appreciably affect the service. The usual arrangement of battery connections is shown in Fig. 34. Taps are brought out from the end cells to a number of terminals arranged to permit the battery to be discharged at the desired voltage.

Connection is made from each end-cell terminal to a bus bar by a sliding contact. The voltage of each cell being about two volts, the pressure delivered by the battery to the bus bar varies according to the position of the sliding contact. When the battery is required to discharge, the sliding contacts are moved toward the outer ends, thus raising the pressure of the battery and causing it to deliver energy to the bus bar. When no energy is required from the battery the end-cell contact is set so that the battery pressure and the bus pres-

sure balance and the battery floats on the system. In case of a reduction in the bus pressure due to a failure in the supply of energy, the battery immediately begins to discharge to the bus, thus tending to hold the pressure up and

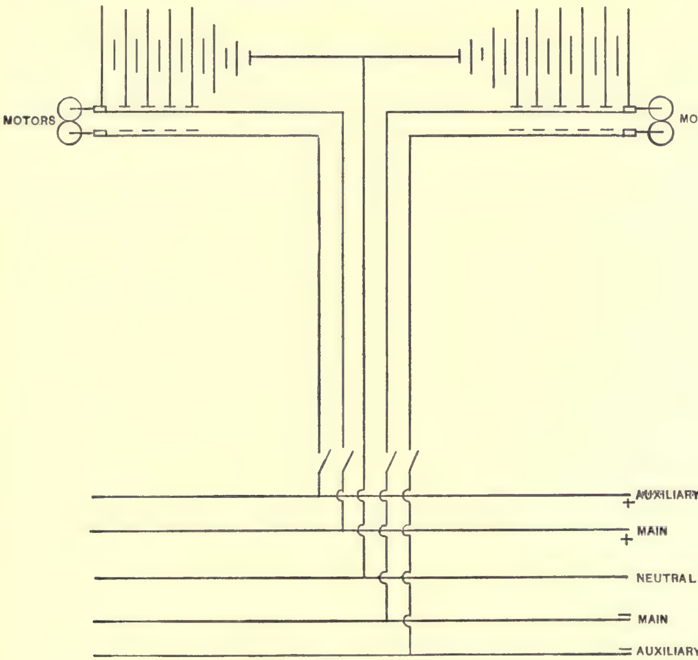


Fig 34. Battery End Cell Connections.

preventing a complete interruption of service. The extent of the interference depends upon the relative capacity of the battery and the load on the bus at the time. During the hours of smaller load the operator's adjustment of the end-cell switches is sufficient to restore the pressure to normal in a very short time, so that the consumer notices nothing beyond a slight flickering in the lights.

The maximum load in a large system is usually considerably greater than the average load, and it is not feasible to provide

sufficient battery to care for a serious accident at the hour of the maximum. The maintenance of batteries being expensive, it is usual to provide about 25 to 40 per cent of the maximum load in battery capacity.

Two or three busses are provided, so that the battery may discharge simultaneously to main and auxiliary busses at different pressures if required. It is desirable to keep the battery floating on the main bus while it is being charged through another bus. The battery may be charged through a booster from the main bus, or from a separate converter or generator wound for the higher pressure required for full charging.

The battery is usually arranged for motor control of the end-cell switches with indicators on the switchboard to show the operator the position of the end-cell switches on each bus, ammeters on each bus and pressure connections by which the voltage of individual cells may be taken.

The most essential points in the construction of a battery station are ample space, proper ventilation and sufficient strength to support the weight of the cells.

The cells are set side by side so that the plates of neighboring cells can be joined together by a lead bar without the use of copper bus-bar work as far as possible. The floor space required by a battery is much more than that which is needed for an equal capacity in converting apparatus. It is sometimes necessary on this account to put parts of a battery on separate floors.

The use of sulphuric acid as an electrolyte, and the ebullition of gases from the battery, tend to keep the air in a battery room heavily laden with sulphuric acid vapor. This acid corrodes all the common metals except lead, as well as many organic substances. It is therefore necessary to protect all structural steel work with building tile and plaster and to keep all copper bus work well painted. As a further means

of reducing the corrosive action ample ventilation must be provided. Where natural ventilation cannot be secured, fans must be provided discharging through a stack. During the summer months open windows may be relied upon where batteries are sufficiently remote from adjoining buildings to

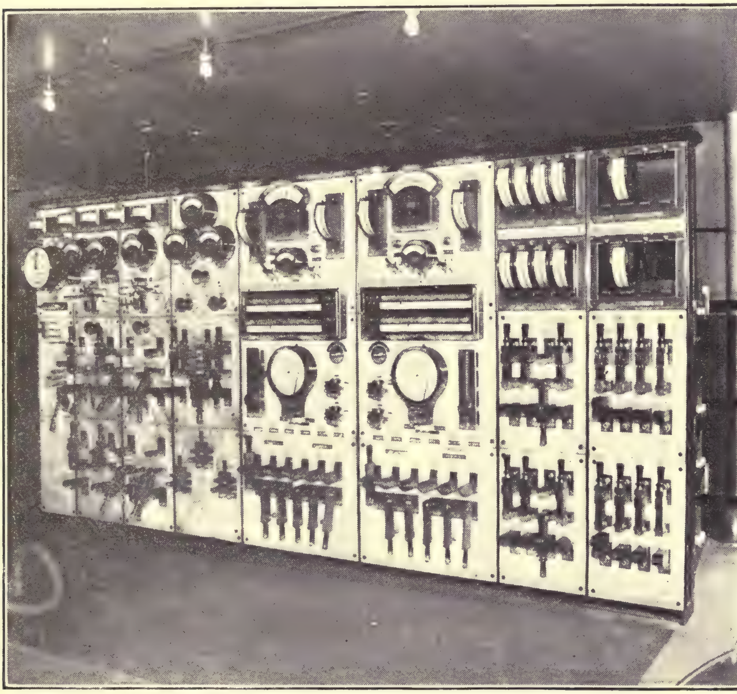


Fig. 35. Storage Battery Switchboard.

avoid interference with the rights of others. The floor of the battery room must be arranged to drain off any leakage of the electrolyte. The use of cement floors is not permissible on account of the action of the acid. It is therefore usual to lay a floor consisting of a layer of roofing paper well coated with compound and over this a floor of vitrified tile brick with the spaces between the bricks carefully filled with com-

pound. Such a floor will not permit the leakage of any electrolyte to the lower floors, and is not affected materially by the acid.

The operation of the battery being affected by the specific gravity of the electrolyte, it is necessary to have a supply of pure water for the purpose of diluting the acid at intervals. The provision of facilities for the storage or manufacture of distilled water is therefore usually necessary.

The end-cell connections are perferably terminated on an end-cell switch built into one wall of the battery room and facing toward the outside. This keeps the strong acid fumes away from the end-cell switch and other substation apparatus. A battery switchboard with end-cell indicators and controlling devices is illustrated in Fig. 35.

CHAPTER IV.

VOLTAGE REGULATION.

THE inherent sensitiveness of the incandescent lamps to variations in pressure necessitates refinements of regulation in electric lighting work which are not required for power or traction purposes. The excellence of a central station's lighting service is determined very largely by the attention given to pressure regulation, and much thought has therefore been given to this subject by engineers from the earliest days of the industry.

In general, the regulation of pressure is accomplished by variations of bus voltage and by control of the pressure on individual feeders.

Low-tension Networks. — In low-tension networks, which are generally operated with direct current, uniform pressure is maintained on the mains by varying the bus pressure as the load changes and by the fact that the regulation of pressure is to some extent automatic. When a heavy load is placed at any point on a network the pressure near that point is lowered somewhat, causing current to flow from all adjacent feeders toward the low point in proportion to the capacity of the mains in the vicinity of the load. The heavy load is thus carried in part by each of the feeders nearest the low point, which tends to support the pressure in that locality. When the adjacent feeders take the added load the pressure at their ends is held by raising the bus pressure, and the system tends thus to automatically equalize the pressure within certain limits.

The different lengths and sizes of the feeders tend, however, to produce higher pressure on the network near the station and lower pressure at remote points during the heavy-load period. In the earlier development of networks it was customary to insert resistances in the feeders to keep the pressure down on the short feeders and to afford means of shifting load from one feeder to another. This practice was discontinued as a general thing because of the inherent tendency of the network to regulate the pressure automatically. The loss of energy in feeder resistances was a considerable item and the space required is considerable where feeder loads are heavy. They are used in modern practice only for very short feeders, where regulation cannot be secured without them.

It is found desirable to provide two or more separate busses and to arrange the switchboard so that the shorter feeders can be carried on one at a lower pressure and the longer feeders on the other busses at higher pressures. Each bus is supplied from a source which can be independently regulated, and each zone may therefore be carried at a pressure suited to average drop on its feeders.

This arrangement necessarily requires a sufficient number of sources of supply of the proper capacity to carry the loads on the several busses, and is therefore only applicable to stations and substations having several units.

The operation of several busses is necessary only during the hours of heavy load since the difference between the drop on the longer and shorter feeders is not so great during the hours of light load, and all feeders can be carried from one bus.

It is often practicable to prevent pressure from running too high during the light-load period by opening a part of the feeders running to a district, transferring the load to the remaining feeders and increasing the drop on them.

With very long feeders it is sometimes necessary to install

a motor-driven booster in series with the feeders to hold the pressure up. Such boosters may be compounded to automatically maintain constant pressure at the feeder end as the load changes. Where storage batteries equipped with end-cell switches are available, it is sometimes feasible to put the longer feeders on the battery through a separate bus and thus avoid the use of a booster. The installation of a booster is not justified until the fixed charges on the cost of the feeder capacity required to produce equivalent results exceed the fixed charges on cost of the booster equipment plus the value of the loss due to its operation.

It is usual in low-tension networks to run pressure wires from the principal feeder ends back to the station where they are connected to a multiple-point switch in such a way that a voltmeter may be connected to the pressure wires of any feeder, and the pressure at any point in the network may thus readily be known at any time.

In operating the system a feeder which represents the average condition in any zone is selected as a standard feeder. The pressure wires of this feeder are run to a separate voltmeter which is used for regulating the bus which supplies the zone. The operator manipulates the field rheostat of the machines which are carrying the load as may be necessary to hold the pressure as indicated by the voltmeter on the standard feeder constant. A similar standard feeder is required for each bus, and in large systems a second standard is often maintained for use in case of emergency.

In stations where a storage battery auxiliary is provided, it is usual to adjust the battery pressure to that of the bus and connect them in parallel. This permits the battery to float on the bus and thus automatically charge and discharge as the pressure rises above or falls below the normal. The effect of this is to steady the bus pressure greatly and to partially sustain it in case of interruption of the power supply.

Alternating-current Networks. — In alternating-current systems the problem of pressure regulation is solved in quite a different way. Individual feeder regulators which waste but little energy permit the economical operation of most of the feeders on one bus if it is desired, though two busses are usually provided for other reasons. In low-tension networks the conditions are very similar to those found in a direct-current network, but the problem is much more easily met because of the availability of feeder regulators. When a feeder becomes overloaded the regulators of adjacent feeders may be used to raise these feeder-end pressures and thus cause these feeders to take part of the load of the overloaded feeders. Where the feeders are low tension as well as the mains, and are installed underground, pressure wires may be embodied in the feeder cables, as is customary in direct-current distribution, at a small expense. If the lines are overhead or the construction is such that separately insulated pressure wires are required, it is usually less expensive to utilize line-drop compensators instead.

Primary Systems. — In areas in which the load is so scattered that the distribution is effected chiefly by means of primary mains, it is usually found desirable not to interconnect adjacent feeders. This requires that each feeder be independently regulated to deliver the proper pressure at its terminus, and feeder regulators are therefore very essential to a system having a number of feeders of different lengths and sizes.

Bus-bar Regulation. — The automatic regulation of bus pressure is desirable where automatic feeder regulation is not used, as the operator can properly care for gradual changes in the feeder load by hand regulation, if the bus pressure is held steady by the automatic devices. It is also desirable in any case where a steady bus pressure is required.

The automatic regulator devised by Tirrill has proved very successful in the control of bus pressures. The general scheme of connections for this device is illustrated in Fig. 36, and the action may be described thus:

The secondary circuits of the potential and current transformers of the generator are led through a solenoid in a compounding relation. The current section is subdivided so that

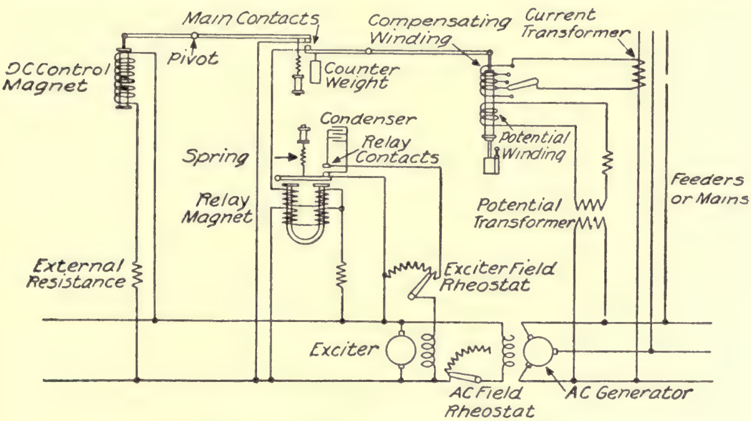


Fig. 36. Tirrill Regulator Connections.

different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other contact terminal of this relay circuit is carried on a similar lever which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main-generator terminals tends to close it. The closing of the relay circuit demagnetizes the relay as the other arm of the relay is continuously excited in the opposite sense.

As soon as the poles of the relay are demagnetized its armature is withdrawn by a spring. This closes a circuit which shunts the field rheostat of the exciter and greatly increases its terminal pressure. This increases the pull of the direct-current solenoid plunger and opens the relay circuit, thus weakening its pull. The result is a rapid vibratory action which is kept up almost continuously. As the load increases, the current winding on the alternating-current solenoid exerts an increased pull on the plunger which causes the lower contact of the relay circuit to move upward toward the other contact and thus close the relay circuit sooner. This raises the exciter pressure, and thereby the generator pressure, until it has been restored to normal. The vibratory action continues as before but the contacts are working in a slightly higher position in space, thus forming a "floating contact."

A condenser is used to diminish the action of the arc at the contact which shunts the exciter rheostat.

The ability of the shunt contacts to break the circuit is the limiting feature of the apparatus. This limit is reached at about 50 kw. on the exciter or 2000 kw. on the generator. Above this two or more breaks must be used in series, each shunting a portion of the exciter field rheostat.

Where there are several units in parallel in a station the regulator may be applied to the exciter for a part of them and the bus regulated for constant pressure, with the series coil of the alternating solenoid cut out. With this arrangement the bus pressure may be maintained constant at any desired point by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

Feeder Regulators. — The design of an efficient and practical form of feeder regulator is fortunately quite feasible, and there are two types in general use in America. Stillwell, in 1888, devised a transformer with a secondary winding tapped

at intervals, the taps being brought out to a dial switch. By the motion of this dial switch handle, more or less of the secondary windings could be thrown in series with the feeder, thus raising or lowering the pressure. A reversing switch was also provided by which the pressure of the regulating transformer could be opposed to the bus pressure if desired. This type is illustrated in Figs. 37 and 38.

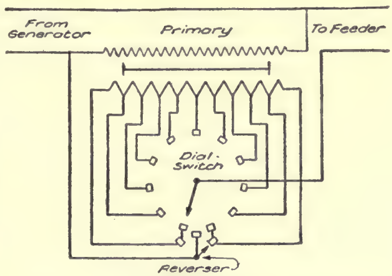


Fig. 37. Transformer-type Regulator Connections.

Another type of regulator which was developed somewhat later is known as the "induction" type.

In this regulator the variable voltage of the secondary is secured by turning the movable core on which the secondary is wound to different positions, thus linking more or less of the magnetic flux. If turned more than 180 degrees the secondary voltage is reversible through its full range.

This type is inferior in efficiency and power factor to the Stillwell type, owing to the presence of an air gap in the magnetic circuit, but its freedom from sliding contacts renders it more suitable for use in cases where remote or automatic control is employed. Fig. 39 illustrates a typical equipment of this class. In this installation the induction regulators are actuated by small three-phase motors mounted on the regulator frames. A reversing switch located on the feeder panel enables the operator to move the regulator in either direction, thus raising or lowering the pressure. A limit switch is provided for the purpose of cutting the motor out when the regulator has been brought around to the position of the maximum boost or choke. Hand control is also pro-

vided for use in emergency. Fig. 40 shows a cross-section view of the induction regulator coils.

Automatic Regulation. — Automatic feeder regulation has been adopted quite generally in conjunction with the use of motor-operated regulators.

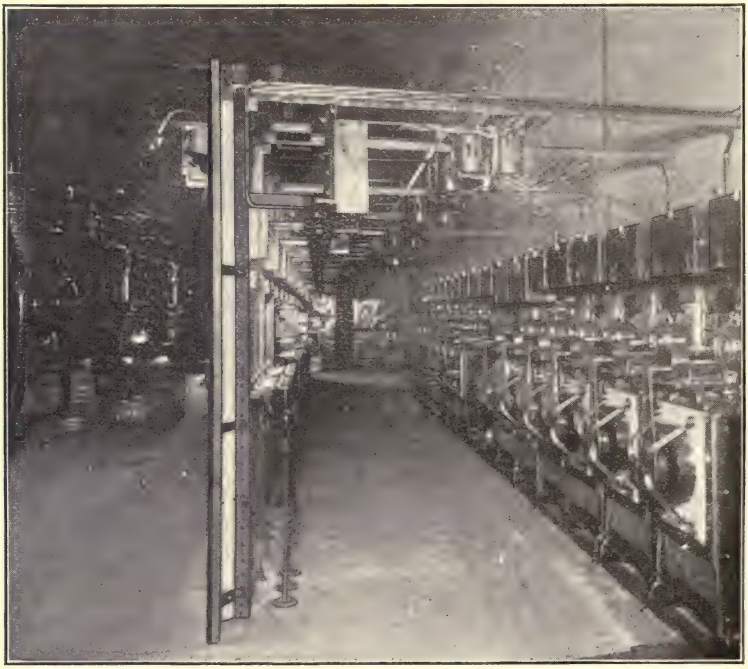


Fig. 38. Transformer-type Regulators.

The use of automatic voltage control is essential to first class service where there are a number of circuits and where the duties of the operator make it impracticable for him to watch the pressure continuously.

This is particularly important with circuits having a mixed power and lighting load, which is continually varying as the power demands change.

The general use of automatic regulation has led to the development of automatic regulators designed for installation out of doors without attendance. These regulators find

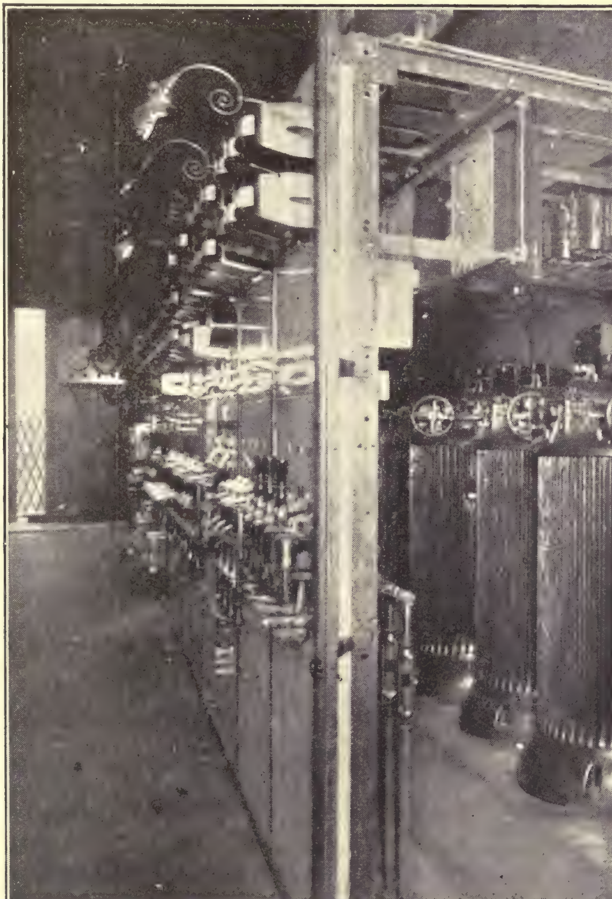


Fig. 39. Induction-type Regulators.

a special field of application in the supply of lighting service to towns and villages which are served from a transmission line by an out door substation.

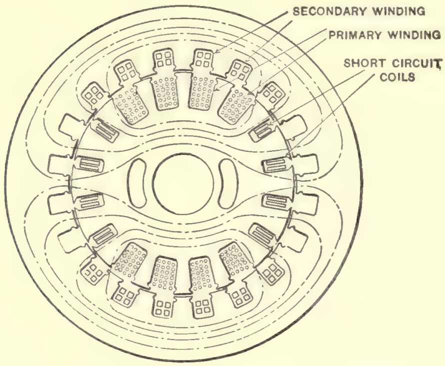


Fig. 40. Section of Induction Regulator.

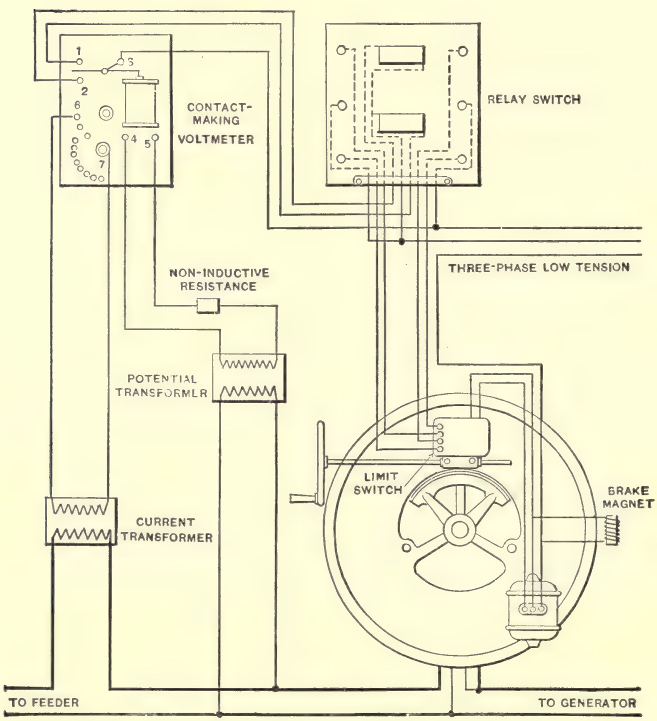


Fig. 41. Connections Automatic Induction Regulator.

The equipment often employed for automatically controlling the pressure on a feeder is shown in Fig. 41. This consists of a motor actuated potential regulator with limit switches to stop the motor when the regulator has reached the limit of its travel in either direction, a relay switch which controls the supply of energy to the driving motor, a contact-making voltmeter, which is devised and adjusted in such a manner as to cause the relay switch to close the motor circuit in the proper direction to raise or lower the pressure, as may be

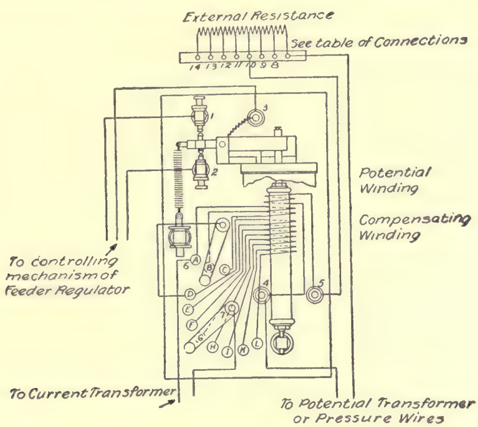


Fig. 42.

necessary, and current and potential transformers, as indicated.

The contact-making voltmeter contains a solenoid wound as shown in Fig. 42, one coil being magnetized in proportion to the pressure on the line side of the potential regulator and the other in proportion to the load carried by the feeder.

This device thus serves the double purpose of compensator and voltage relay for circuits which do not require inductive compensation.

In this device, the constant pull, due to the standard feeder end pressure on the core is balanced against a spring.

A series winding on the same solenoid carries current in proportion to the load on the feeder. The action of the series coils is opposed to that of the voltage coil and the result is that as more load is carried on the circuit, the pressure impressed upon the voltage coil must be increased in order to maintain a state of equilibrium on the contact-making lever. With the proper number of series turns cut in, the pressure is automatically kept constant at the feeder end within 1 to 2 volts, at all loads.

The series coil is arranged in sections, two points being about 10 per cent each and eight points being about 1 per cent each. Thus the "contact making voltmeter" may be set to compensate for any feeder drop by steps of one per cent up about 30 per cent.

The voltage coil in the contact making voltmeter is provided with an adjustable external resistance so that the device can be set for any desired standard pressure by steps of five volts. Intermediate adjustments are made by varying the tension on the spring against which the voltage is balanced.

With circuits whose load is so largely made up of lighting that their power factor is 90 per cent or higher, this form of compensator is found quite satisfactory and no separate line drop compensators are needed.

In manufacturing districts where feeders carry loads with power factors of 70 per cent to 80 per cent, the inductive drop on the circuit becomes a considerable factor and line drop compensators are usually provided where good service is required.

When compensators are used, the series coils on the contact making voltmeter are not employed as the desired effect is produced upon the solenoid by the pressure coil alone, acting in conjunction with the opposing springs which control the contact lever. The pressure impressed upon the

solenoid is compensated so that it represents the feeder end pressure. As this is to be kept constant, the spring may be set to offset a constant pull. When the feeder end pressure varies by 1 to 2 volts, or more, from the standard, contact is made by the levers, thus operating the regulator and restoring the pressure to normal. When the compensator is properly set, the feeder end pressure is thus automatically maintained constant within a few volts.

The scheme of connections for automatic regulation with contact making voltmeters and line drop compensators is shown in Fig. 43.

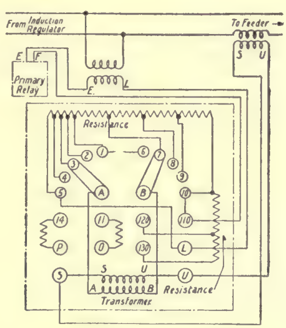


Fig. 43.

The current from the secondary main current transformer of the circuit enters the compensator windings by way of the dial switch, and the voltage circuit is tapped at the points where the series coils are connected in the voltmeter type of compensator. The adjustment of the dial switch is made as in the voltmeter type. In case it is desired to maintain an indicating voltmeter in the circuit, as well as the voltage regulating coil, the voltmeter must be specially calibrated to correct for the constant drop in the compensator coils.

Line Drop Compensators. — The function of the line-drop compensator is to introduce into the feeder voltmeter circuit

a counter E.M.F. which reduces the reading of the voltmeter by an amount equivalent to the line drop, and therefore indicates to the station operator the pressure delivered at the feeder end. The compensator circuit is a miniature of the feeder itself, the pressure transformer representing the bus bar, the compensator the line, and the voltmeter the load. Since the feeder has both resistance and inductance, the compensator has two sections, one representing the ohmic and the other the inductive drop in the main circuit.

These sections are each provided with a dial switch by which sections may be cut in or out so that the compensator may be set to maintain a correct indication of the pressure at the end of a feeder at any power factor, or at any distance within its range of compensation. The sections are so selected that rough adjustments of 5 per cent and fine adjustments of 1 per cent may be made in the types made by the Westinghouse Electric Manufacturing Company. The General Electric Company's compensators are designed for a range of 24 per cent with eight points having a value of 3 per cent each.

Compensators are used with hand operated regulators in connection with an indicating voltmeter for the guidance of the operator, and with automatically controlled regulators with or without an indicating voltmeter. The indicating voltmeter is not required with automatic control under normal conditions as the operator depends entirely upon the automatic devices to keep the pressure normal. But in case part of the equipment becomes inoperative it is necessary to control the regulator manually and in this event it is necessary to have a voltmeter accessible which can be connected to take the place of the equipment which is in trouble.

The relation of parts and scheme of connections of a West-

inghouse compensator of the indicating voltmeter type is shown in Fig. 44.

The current from the secondary of the current transformer *S* passes through the inductive section *B* and the noninductive section *A* in proportion to the load on the feeder. The

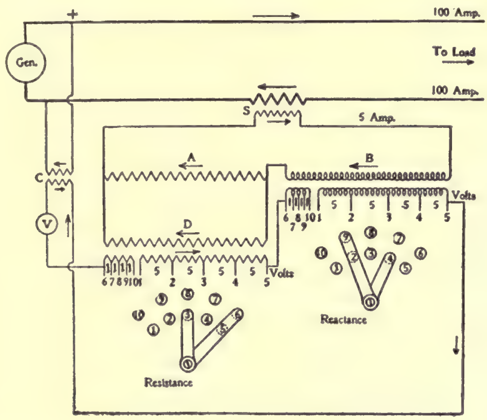


Fig. 44.

ratio of the current transformer must be such that at its full load the current in the secondary will not exceed 5 amperes.

The secondary winding is divided into four sections of five volts each, and four of one volt each. The five-volt terminals are connected to the contacts numbered 1, 2, 3, 4 and 5, and the one-volt terminals to the contacts numbered 6, 7, 8, 9 and 10. The arms may be independently adjusted, thus permitting any setting from 1 to 24 to be made, as in the table on the following page.

The noninductive section is similarly equipped and the settings are made in the same way.

The pressure from the main pressure transformer *C* passes through the feeder voltmeter to terminal 6, through the two movable arms to 3, through the portion of the noninductive section, which is included between 3 and 5, thence through

Switch points.	Per cent compensation.	Switch points.	Per cent compensation.
5-6	0	3-9	13
5-7	1	3-10	14
5-8	2	2-6	15
5-9	3	2-7	16
5-10	4	2-8	17
4-6	5	2-9	18
4-7	6	2-10	19
4-8	7	1-6	20
4-9	8	1-7	21
4-10	9	1-8	22
3-6	10	1-9	23
3-7	11	1-10	24
3-8	12	....	....

the inductive section by a similar path through the portions between 9 and 6, and between 4 and 5. It then returns to

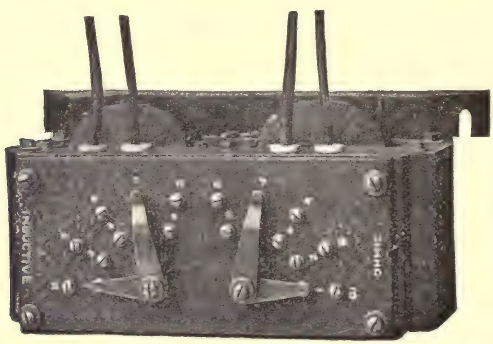


Fig. 45. Westinghouse Line Drop Compensator.

the pressure transformer. In making this circuit the impressed pressure has been opposed by a counter E.M.F. of 10 volts in the noninductive section and by 8 volts in the inductive section.

The reading of the voltmeter is therefore reduced by the same amount as would be a voltmeter connected at the end

of a feeder having a resistance drop of 10 volts (secondary) and a reactance drop of 8 volts at full load.

The general external appearance of this type of compensator is illustrated in Fig. 43.

The general scheme of connections of the compensator, as worked out by the General Electric Company, is illustrated in Fig. 46.

In this type the current from the main current transformer at maximum load is reduced from 5 amperes to 1 ampere by

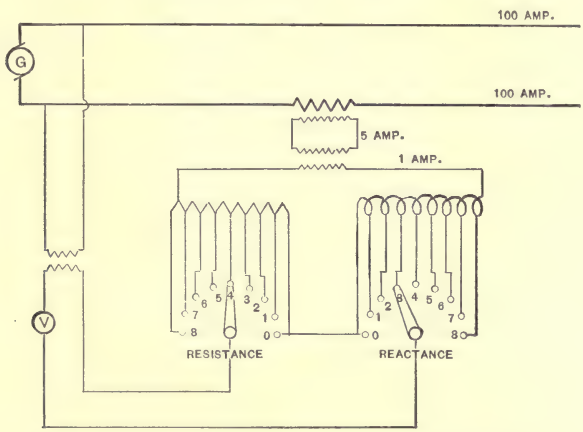


Fig. 46. General Electric Compensator Connections.

a current transformer inside the case of the compensator. There is but one movable arm on each section and 8 points each of which represents 3 volts when 1 ampere is flowing in the compensator.

The compensator shown in Fig. 46 is set so as to introduce in the voltmeter circuit an inductive counter E.M.F. of 9 volts and a noninductive counter E.M.F. of 12 volts when the feeder is carrying full load.

The points being numbered, the operation of setting is easily accomplished without reference to a table of settings,

corresponding to various percentages of compensation. The general appearance of this type is shown in Fig. 47.

Calculation of Compensator Settings. — With a feeder of No. 0 wire, 5000 feet long, single-phase, overhead wires 12

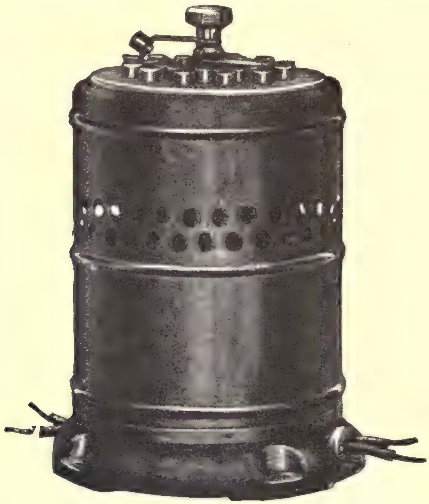


Fig. 47. General Electric Line Drop Compensator.

inches apart, pressure 2200 volts at feeder end, frequency 60 cycles, current transformer rated 100 to 5 amperes, pressure transformer rated 2200 to 110 volts, how should the compensator be set?

The full-load rating of the compensator being 5 amperes that of the feeder is 100 amperes. The ohmic drop on a No. 0 feeder at 100 amperes is .2 volt per ampere per 100 feet of two-wire circuit. Hence the ohmic drop is $100 \times 5 \times .2 = 100$ volts, or 4.5 per cent. Likewise the inductive drop is .22 volt per ampere per 1000 feet, and the inductive drop on the feeder $100 \times 5 \times .22 = 110$ volts, or 5 per cent.

These values may be found for various sizes of wire in Table XXI, Chapter XVI.

If the primary mains are designed to give about 2 per cent ohmic drop, the transformers 2.0 per cent and secondary mains 2 per cent, the average ohmic drop from the feeder end to the consumer's premises would be about 3 per cent. The inductive drop would also be about 3 per cent. These average drops are applicable to the major portion of the distributing mains, and they may be added to the drop on the feeder and the compensator set so that the drop on both feeder and distributing system will be taken into account. The pressure may thus be regulated to give constant pressure at the average consumer's premises. In this case the total ohmic drop is $4.5 + 3 = 7.5$ per cent, while the inductive drop is $5 + 3 = 8$ per cent.

If a Westinghouse 24 per cent compensator were used, the setting of the resistance section would be $7\frac{1}{2}$ per cent of 110, or 8 volts, and of the reactance section 8 per cent of 110, or 9 volts. The resistance arm would therefore be set at 4–9 and the reactance section 4–10. The operator keeps the feeder voltmeter at 110 volts at all loads, assuming this to be the standard pressure.

With a General Electric compensator having 8 points on each part, the points have a value of 3 volts each, and in this case the arm of each section would therefore be set at the third point.

On a two-phase four-wire feeder the method of connection is similar to that used in the single-phase feeder, except that one equipment is required for each phase. The method of calculating the setting for each phase is the same as in the case of a single-phase feeder. With a three-wire two-phase feeder, with unbalanced load one compensator is required in each of the three wires. The connections should be as shown in Fig. 48, when the load is unbalanced.

In calculating settings it must be borne in mind that the values of resistance and inductance per 1000 feet used in

the case of a single-phase feeder are based on two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only. The values used for single-phase feeder resistance must therefore be divided by two before

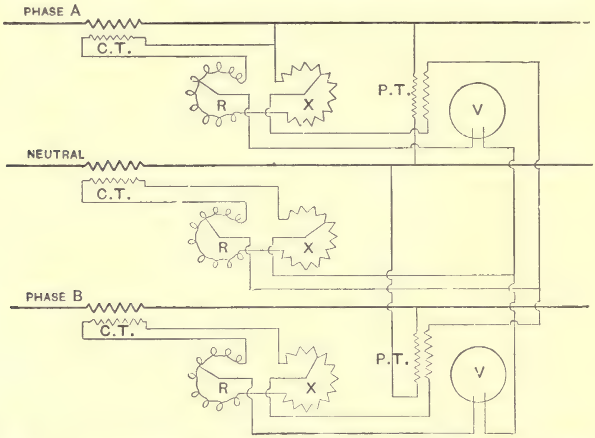


Fig. 48. Compensator Connections Two-phase Three-wire Circuit.

being applied to a three-wire feeder whether two-phase or three-phase.

In case the common wire is equipped with a current transformer having a higher ratio than the other wires, or if the common wire is larger than the other wires, the proper values must be used for this conductor. The allowance made for drop in the primary mains, transformers, secondaries, etc., should be added to the calculation for the phase wires only of the feeder as it is in phase with the drop in these wires.

With a two-phase feeder of three No. 0 wires similar in other respects to the single-phase feeder previously described, and with a current transformer in the middle wire rated at 150 to 5 amperes, the ohmic drop in the middle wire would be $5 \times 150 \times .1 = 75$ volts, or 3.5 per cent, and the inductive drop would be $5 \times 150 \times .11 = 82$ volts, or 4 per cent. The

drop in the outer wires would be $5 \times 100 \times .1 = 50$ ohmic and 55 inductive, or about 2.5 per cent. Adding the allowance of 3 per cent for drop in the distributing mains, the compensator on the outer or phase wire should be set at 6 per cent on each dial of the compensator. The compensator on the middle wire should be set at 4 per cent on each dial.

In the case of a three-wire three-phase feeder, the connec-

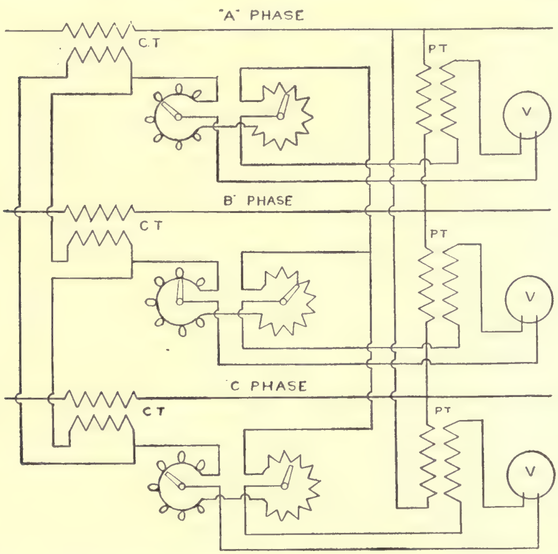


Fig. 49. Three-phase Three-wire Compensation, Star Connected.

tions of compensators and voltmeters are as illustrated in Fig. 49. It will be seen that the compensators are star-connected and the voltmeter transformers are delta-connected.

By this arrangement, the current in the compensators is brought into phase with the line pressure, since the current in the line wire is 30 degrees ahead of the line pressure, and with the secondaries of the current transformers in delta, the resultant current passing from them into the compensator is again thrown forward 30 degrees. This brings the current

180 degrees from the impressed pressure, when the load is approximately balanced on the three phases. The current passing through the compensators is 1.73 times that in the series transformer coils and this must be allowed for in calculating the compensator settings as follows: If full-load current on a No. 0 feeder is 100 amperes, the ohmic drop per wire was found above to be $5 \times 100 \times .1 = 50$ volts at 5000 feet distance, and the inductive drop to be 55 volts. These values must be divided by 1.73 in order to derive a compensator setting which will be proportional to the current in the compensator coils.

When the current in the line is 100 amperes, the current in the compensator is not 5 amperes but $5 \times 1.73 = 8.66$ amperes. It therefore introduces a counter E.M.F. in the voltmeter circuit which is not proportional to the line drop, unless reduced by dividing the setting by 1.73. The ohmic setting in this case would therefore be $50/1.73 = 29$ volts, or 1.3 per cent and the inductive setting would be $55/1.73 = 32$ volts, or 1.4 per cent.

This result may be secured by connecting each compensator into the secondary circuit of its corresponding line current transformer separately, and connecting the primaries of the potential transformers in star, as shown in Fig. 50. By this plan the potential transformers must have a 58 per cent tap on the primary winding, or special resistance coils in the voltmeter circuit, if standard 110 volt potential indicating instruments are used. This necessitates apparatus of non-standard ratios, which is undesirable in the average installation, and the method by which the compensators are star-connected is usually considered preferable.

Where automatic regulation is employed, using devices such as the contact-making voltmeter, the pressure coils of the device are treated as voltmeters and the current coils as compensators in making up the diagram of connections.

The allowance for drop in distributing mains must be divided between any two compensators, as it is in phase with the working pressure. 1 per cent should therefore be added to the 1.3 per cent ohmic and 1.4 per cent inductive drops,

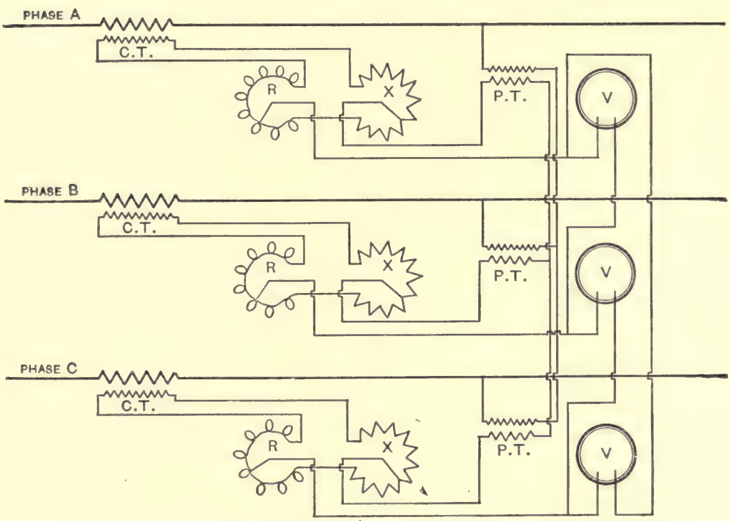


Fig. 50. Three-phase Three-wire Compensator Delta Connected.

making the ohmic setting 2.3 per cent and that of the inductive 2.4 per cent.

In a three-phase four-wire system operating at 2200 volts between each phase and the neutral, the method of calculating the drop is as follows: With a feeder of four No. 0 wires running 5000 feet from the station as a three-phase feeder, the drop in each wire is 50 volts ohmic and 55 volts inductive. The working pressure being 2200, this is 2.5 per cent. If the entire load of the feeder is delivered from this center of distribution the compensator on each phase wire should be set at 2.5 + 3.0 = 5.5, or say 6 per cent on each dial. That on the neutral should be set at 2 per cent on

each dial. If, however, the A-phase branches off with a neutral to a single-phase center of distribution 2000 feet beyond, there must be added to the A-phase setting $100 \times 2 \times .2 = 40$ volts = 2 per cent, making it 8 per cent on each branch. If the other phases branch to similar centers of distribution, at different distances, the drops must be figured as if they were single-phase feeders from the end of the three-phase transmission to the single-phase center of distribution. These

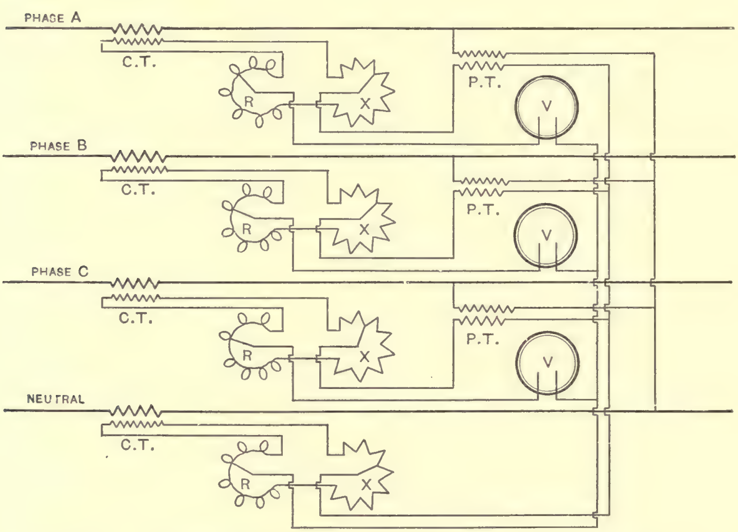


Fig. 51. Compensator Connections Three-phase Four-wire Circuit.

drops must then be added to the three-phase drop above calculated. On four-wire 2300–4000 volt feeders which reach the limit of three-phase transmission within 3000 feet of the station, it is usually unnecessary to install a compensator on the neutral wires, as the neutral drop is negligible, even with a considerably unbalanced load.

The connections of compensators for a four-wire three-phase feeder are shown in Fig. 51.

Compensator Settings, Non-Inductive Type. — In making trial settings of the non-inductive type of compensators or of the General Electric contact-making voltmeter an allowance must be made for the effect of the inductive component of drop. Having calculated the ohmic and inductive component of drop, the impedance volts are the resultant of the two, $Z = \sqrt{R^2 + X^2}$. For the sizes and spacing of conductors usually found in distributing feeders the impedance may be considered as substantially equal to the actual drop at power factors of 85 per cent to 95 per cent.

For instance, with a No. 0 feeder carrying 100 amperes at a distance of 5000 feet under conditions as described on page 100 the ohmic drop is 100 volts, or 4.5 per cent and the inductive drop is 110 volts, or 5 per cent. The impedance is therefore $\sqrt{(100)^2 + (110)^2} = 148$ volts $= 6.7$ per cent.

If the resistance type of compensators were set at 6 per cent as a trial setting, it would be found to be very near the correct setting to give regulation within 1 per cent of the standard value at all loads. The contact-making voltmeter would be set in a similar manner.

The final adjustment should be made by comparison with 24-hour charts from a recording voltmeter at the feeder end with either of these types of apparatus.

CHAPTER V.

LINE TRANSFORMERS.

The transformer is perhaps, next to the generator, the most important piece of apparatus which the electrical engineer has at his disposal. Without it the development of alternating-current transmission and distribution systems would have been so greatly restricted that the use of electricity could never have reached the proportions of the present. Distribution would have been limited to lower voltages and transmission would not have passed beyond the limits within which generators and motors may be wound.

The transformer is the simplest piece of apparatus which is employed in electrical engineering. With no moving parts it is a mere combination of copper and iron which needs but the application of an electromotive force at its terminals to make it instantly operative.

The physical phenomena which take place in the transformer are, however, not as simple as its construction.

When pressure is applied to the terminals of the primary winding with the secondary circuit open, the current which flows is known as the leakage current. The leakage current is made up of two components, known as the magnetizing component and the iron loss component. The magnetizing component is that portion of the leakage current which induces a magnetic field in the iron core. The iron loss component is that portion which supplies the energy losses in the iron core.

The magnetizing component is a quarter cycle behind the impressed voltage wave, while the loss component is in phase

with it. The leakage current L is therefore $\sqrt{M^2 + I^2}$, in which I is the iron loss component and M is the magnetizing component. M is about twice as great as I in distribution transformers of 2 to 50 kw. capacity. The leakage current is readily determined from ammeter readings, while the iron loss may be found by the use of a suitable wattmeter. From these the magnetizing component may be readily calculated from $M = \sqrt{L^2 - I^2}$.

The secondary voltage is a quarter cycle behind the wave of core magnetism, which brings it a half cycle behind the primary impressed pressure, or in opposition to it. The ratio of the primary to the secondary voltage is called the ratio of transformation.

When current is permitted to flow in the secondary circuit, the magnetomotive force set up in the core causes current to flow in the primary of such strength that its magnetomotive force is equal to that set up by the secondary current. For instance with 100 amperes in a secondary having 100 turns, the magnetomotive force is 10,000 ampere turns. If the primary has 2000 turns the primary current will be such as to cause 10,000 ampere turns in it. The primary current will therefore be 5 amperes plus the leakage current when the secondary is delivering 100 amperes.

Ratio of Transformation. — The ratio of transformation of a transformer is fixed by the ratio of the number of turns in the primary to the number in the secondary. That is, a transformer receiving energy at 2000 volts and delivering it at 200 has ten times as many turns in series in its primary coils as there are in series in its secondary coil. When a transformer is wound with two or more sections in its primary or secondary coils, its ratio of transformation can be changed by changing the connections from series to parallel. For instance, in a 1100–2200 to 110–220 volt transformer, there

are four possible combinations of connections, viz., (*a*) primary and secondary sections both in parallel 1100 to 110 or 10 to 1, (*b*) primary in parallel, secondary in series 1100 to 220 or 5 to 1, (*c*) primary in series, secondary in multiple 2200 to 110 or 20 to 1 and (*d*) primary in series, secondary in series 2200 to 220 or 10 to 1.

It is usual to make the primary winding of line transformers interchangeable so that they can be used on either 1100 or 2200 volt systems. The secondary windings of line transformers are divided so that they can be used in three-wire distribution in sizes above one kilowatt.

Transformers designed for transmission service are frequently made with several coils on both primary and secondary to permit their being connected in series for use on higher voltages later as the system develops.

The ratio of transformation is also sometimes made adjustable by steps of 5, 10 or 15 per cent, by bringing taps out from one of the windings of the transformer by which the pressure may be raised or lowered as conditions may require. Such taps are often specified in ordering transformers which are to be used where it is expected to raise or lower the transmission voltage later as the load changes.

The ratio of transformation expressed in terms of the ratio of the number of turns in the coils is strictly true only when the transformer is carrying no load. The resistance and inductance of the windings cause a reduction in pressure of 2 to 3 per cent when the transformer is carrying full load, thus modifying the ratio of transformation slightly.

Leakage Current. — The ratio of the number of turns in primary and secondary being fixed by the voltages of supply and delivery, it is necessary for the designer to fix the number of turns in one of the coils arbitrarily. This number must be high enough to furnish the magnetizing force for the core

without requiring too much leakage current. This leakage current in line transformers should not exceed 3 per cent of normal full-load current except in the smallest sizes, as there are many of them on a distributing system. The combined leakage current in a large system, having a power factor of 50 to 60 per cent tends to interfere with the regulation of the generator pressure, and to increase the energy required for excitation of the fields during the hours of light load.

On the other hand, an increase in the number of turns requires a greater length of wire, which in turn tends to increase the cost of the transformer and reduce its efficiency. The number of turns must therefore be selected so that the leakage current and length of wire will be within proper limits.

Calculation of Windings. — The fundamental formula by which the induced voltage of a transformer is calculated illustrates these facts. The induced voltage of a transformer is $E = \frac{4.44 fnF}{100,000,000}$, in which f is the frequency in cycles per second, n the number of turns in series in the coil and F the total magnetic flux in the core, at the maximum point of the wave. For 60 cycles and 2080 volts this becomes

$$2080 = \frac{4.44 \times 60 \times nF}{100,000,000}, \text{ or } nF = 781,000,000.$$

It is apparent that either the number of turns must be assumed to find the total flux, or the flux may be assumed to find the number of turns. The number of turns fixes the weight of copper and the copper loss, while the magnetic flux fixes the weight of iron and the iron loss.

It may seem at first sight that the area of the cross-section of the iron core would be about the same for all transformers designed for a given voltage without regard to size, since the

product of the turns and the flux is a constant which is fixed by the voltage.

However, the exciting current may be made proportional to the kilowatt capacity and this permits the number of turns to be reduced in the larger units, thus increasing the amount of iron in the core. For instance, in a 2-kw. transformer designed for 2080 volts there would be required about 1900 turns in the primary to keep the exciting current down to a proper amount. The total flux would therefore be $F = 781{,}000{,}000/1900 = 411{,}000$ lines. In a 20-kw. unit, the full-load current being ten times greater, the exciting current may be several times greater. Reducing the primary to 600 turns, the total flux will be $781{,}000{,}000/600 = 1{,}300{,}000$ lines. The average length of a turn is increased because of the greater cross-section of the core and the length of wire is therefore not reduced in proportion to the reduction in the number of turns. A number of trial calculations must be made with different ratios of turns to flux until the most economical combination is found for each size.

The total magnetic flux being determined the area of the cross-section of the magnetic circuit is fixed by an arbitrary assumption of magnetic density per square inch. This value depends upon the character of the core material and may be varied 15 or 20 per cent from a mean value in order to produce consistent designs.

Iron Loss. — The iron loss varies as the 1.6 power of the magnetic density. The law governing this was discovered by Steinmetz and is

$$\text{Iron loss} = \frac{KfVB^{1.6}}{10{,}000{,}000},$$

in which f is the frequency, V the volume of the iron, B the number of lines per unit of area and K a constant depending on the kind of iron used.

It is evident from this formula that as the density is increased the core loss increases more rapidly. On the other hand, if the density is greatly decreased the weight of iron is increased and the cost goes up.

In the smaller sizes of 60-cycle transformers, where the weight of iron is small in proportion to the copper, the density is made lower so as to partly equalize this disparity. The iron in units of 1 to 5 kw. is operated at from 40,000 to 45,000 lines per square inch. In the larger sizes it is made 45,000 to 50,000, and in transmission units as high as 60,000 lines per square inch.

At 25 cycles the total flux for a given voltage must be greater and this tends to require greater cross-section. The iron loss, however, falls off with the frequency, and the density may be increased enough to make up for the decrease in loss at the low frequency. This permits the design of 25-cycle units at densities of 60,000 to 90,000 lines per square inch.

On the other hand, 125-cycle units are usually operated at 30,000 to 40,000 lines. The density having been assumed, the area of the core is $A = \frac{F}{B}$, or $\frac{1,300,000}{50,000} = 26$ square inches in a 20-kw. unit.

Magnetizing Current. — The magnetizing component of the leakage current for a given design may be computed from the formula $C = \frac{BL}{4.44\,NP}$, in which B is the number of lines of force per square inch, L the length of the magnetic circuit in inches, N the number of turns and P the permeability of the iron. Assuming a magnetic density of 50,000 lines per square inch and a permeability of 2000, the magnetizing component of the leakage current would be

$$C = \frac{50,000 \times L}{4.44 \times 2000 \times N} = \frac{5.63\,L}{N},$$

or assuming the magnetizing current, the number of turns is

$$N = \frac{5.63\ L}{C}.$$

The number of primary turns and total flux of various sizes of 2200-volt distribution transformers are approximately as given in the following table:

K.W. Cap.	1	2	3	5	7.5	10	15	20	25	30	40	50
Mega lines	.26	.411	.550	.700	.88	1.02	1.2	1.35	1.45	1.53	1.7	1.85
Turns	3000	1900	1420	1100	890	780	650	580	550	510	460	420
Area of core ..	6.5	9.5	12.2	15.5	17.6	21	23.5	26	27	28	31	34

The formula $E = \dfrac{4.44\ nfF}{100,000,000}$ has been applied numerically in the foregoing only to units designed for 2080 volts and 60 cycles. It is apparent that for higher voltages the product nF will be proportionately higher and that more iron and copper will be required to construct a transformer of given capacity as the voltage is increased. Likewise, if the frequency is lower, the product nF is proportionately higher and more copper and iron is required to construct a transformer of given type and size in direct proportion. On this account 25-cycle transformers and induction motors require more material than the similar types of 60-cycle apparatus and cost more to build.

Types of Core. — There are two general types of arrangement of the windings and core of a transformer. One is known as the shell type, the other as the core type.

In the shell type the coils are threaded through the magnetic circuit and are surrounded by it, while in the core type the coils surround the core. The usual form taken by the

shell type is that shown in Fig 52. It has been used to some extent in line transformers and very generally in connection with synchronous converters where air cooling is employed. The core type shown in Fig. 53 has been used very generally

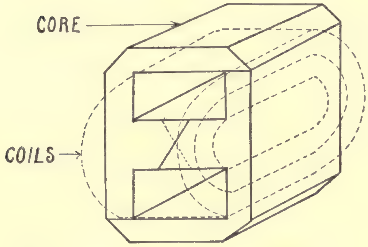


Fig. 52. Shell-type Transformer.

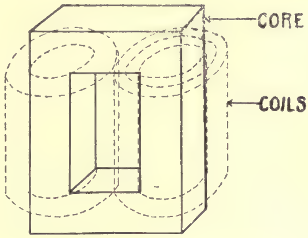


Fig. 53. Core-type Transformer.

for line and transmission purposes where oil cooling is relied upon. The cylindrical form of the coils lends itself to dissipation of heat and application of insulation more readily than the flat type of coil used in the shell type. The core type has therefore been used very generally for distribution purposes.

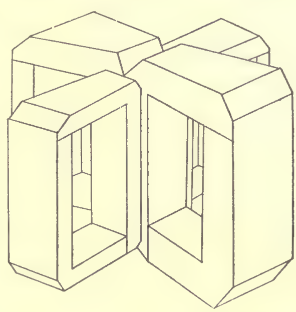


Fig. 54. Cruciform Shell-type Transformer.

In later years a modification of the shell type shown in Fig. 54, known as the cruciform type, was developed, which permits the retention of the cylindrical form of coil with the shell type of core. This form, which has been adopted by two leading American manufacturers, reduces magnetic leakage to a minimum, improves regulation and makes a very compact and efficient arrangement of copper and iron.

In the construction of the magnetic circuit of the transformer the iron must be in sheet form to reduce the flow of eddy currents which tend to be set up by alternating mag-

netic flux. The sheet iron is commonly about .012 inch thick, this thickness having been found to be the most effective and economical. The shape of the stampings of sheet metal is carefully worked out so that they may be built up around the form-wound and insulated coils with facility. This must be done so as to affect the reluctance of the magnetic circuit as little as possible. The alternate laminations are therefore usually overlapped so that the magnetic lines of force do not have to cross a butt joint. The laminations are secured in position by bolts holding them rigidly in place.

Core Material. — The art of manufacturing sheet iron for use in making laminated magnetic circuits for alternating-current apparatus has made progress very steadily from the beginning of the industry. In the early years of alternating-current development the electrical manufacturer had nothing at his disposal in the way of sheet iron except the standard grades turned out for general purposes. It was found very soon that such iron when used in a transformer had magnetic properties which were variable with the length of time in service. The hysteresis loss per pound was high because of lack of proper annealing and varied widely in different lots because of the lack of uniformity in the heat treatment in the mill. The result was that a transformer which was reasonably efficient at the date of manufacture passed through a process of ageing which left it with a greatly increased hysteresis loss and reduced its all-day efficiency very materially. As soon as this phenomenon became well established, an endeavor was made to discover the cause of the ageing. The continued operation of the iron at higher than normal atmospheric temperatures seemed to be the seat of the trouble, and experiments were therefore directed along the line of careful control of the heat treatment of the sheet metal during the process of manufacture to insure as perfect annealing as possible in

the finished product. The accumulated experience of years has produced gradual improvement in the magnetic properties of sheet iron, though ageing has not been entirely eliminated in pure sheet iron.

The manufacture of sheet metal from an iron and silicon alloy has reached a stage where transformers are being manufactured with cores of this metal which not only permits the use of less core material but reduces the core loss and practically

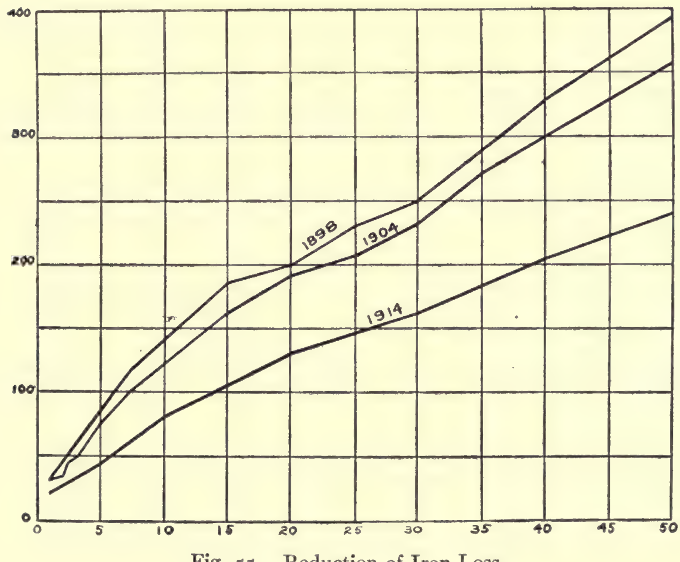


Fig. 55. Reduction of Iron Loss.

eliminates the ageing effect. Manufacturers of transformers have thus been able to reduce the cost of construction and produce more efficient apparatus.

The progress which has been made during the years 1898 to 1914 is made very plain by the curves in Fig. 55, which show the iron losses in the various sizes of line transformers during this period.

Copper Losses. — The copper losses of the transformer add to the production of heat while it is carrying load, and they must therefore be so limited as to keep the temperature of the interior of the transformer from rising more than 50 degrees C. above the surrounding air.

The elevation of temperature is determined by the radiation factor and by the energy losses. In an air-blast transformer, for instance, the dissipation of energy takes place more rapidly than in an oil-cooled unit because special facilities are provided for carrying off the heat generated.

The selection of cross-sections of copper for the windings is therefore fixed within certain limits by the heat losses therein, and by the means provided for their dissipation.

In the small sizes the large number of turns and the very small current in the primary coil allow the use of a lower current density than is permissible in the larger sizes.

In the sizes above 5 kw. the copper is usually run at from 400 to 500 circular mils per ampere at full load. These densities give full-load copper losses which are somewhat greater than the iron losses in the smaller sizes, while they amount to about twice the iron losses in the larger units.

Heat Dissipation. — The problem of disposing of the heat generated in a transformer is one which has required a great amount of study and experiment. In the beginning of the art when units were small, natural radiation into the air was sufficient. As sizes increased this was inadequate to keep down interior temperatures to a point where deterioration of insulating materials would not take place. The air blast was naturally suggested as a means of hastening radiation and has found a useful field in stations and substations where attendance is continuous and floor space is limited.

This is not feasible, of course, for distribution work, and the use of a bath of oil around the coils was tried. This

served the double purpose of excluding moisture and assisting radiation by the action of convection currents which cause the heated oil next to the coils to rise to the top, drawing the cool oil up from the bottom to take its place. This plan was soon found to be so effective both in cooling and

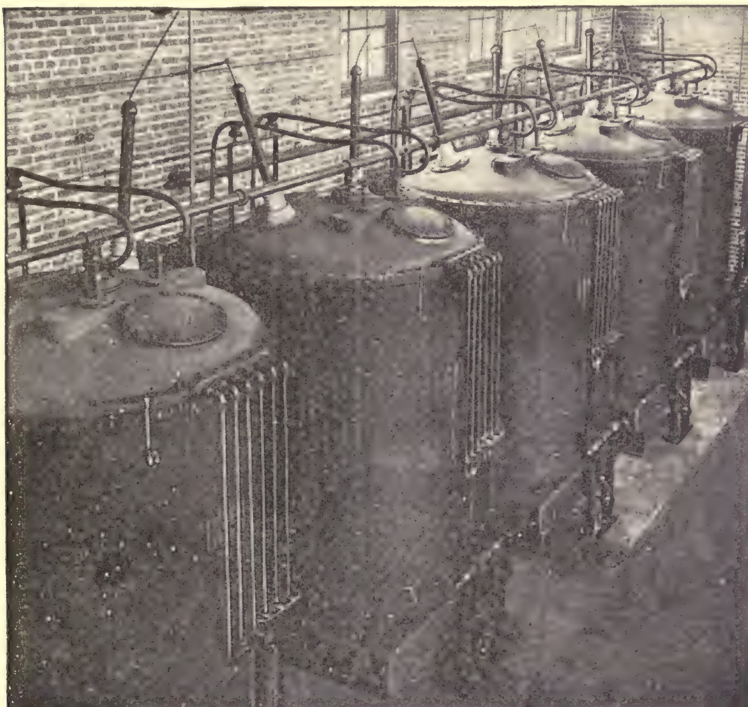


Fig. 56. Water-cooled Transformers.

insulating the coils that it became standard practice with all the principal manufacturers, and continues to be the method used for all line transformers and for station work where floor space is not limited or where the voltage of transmission is above 15,000. In units of over 500 kw. the size of the case necessary to hold oil sufficient to radiate the energy at

the proper rate becomes excessive. It is therefore usual to provide a case of sufficient size to contain the transformer and cooling coils of pipe as shown in Fig. 56. The transformer and cooling coils are immersed in oil which serves to convey the heat from the transformer below to the coils above. Water is circulated through the cooling coils in proper quantities to carry away the heat liberated in the transformer. This method of cooling is readily applicable where a cheap supply of water is available. It may not be economical where a supply of water must be purchased at usual municipal water rates.

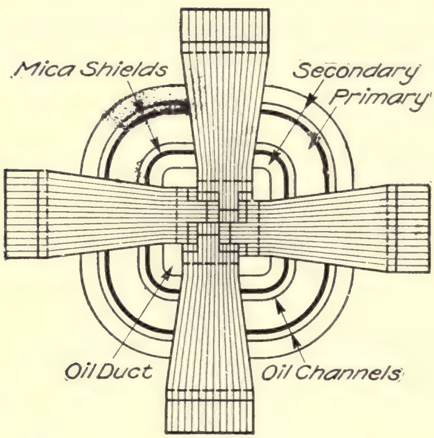


Fig. 57. Arrangement of Oil Ducts in Transformer.

In very large units, 2500 kw. and over, it is necessary to provide a forced circulation of water or oil to carry away the heat.

In the design of the coils and cores of self-cooled oil-insulated transformers, it is important that they be so shaped and mounted on the core as to permit a free circulation of oil about them. For instance, in the core-type transformer the square corners are used in conjunction with the cylindrical coils to provide open vertical channels or flues through which

streams of oil may pass, thus reaching the inner parts of the coils and core, and preventing these parts from reaching a temperature very much higher than the outside parts as shown in Fig. 57.

In the shell type this is not feasible, and radiation must be accomplished by flaring apart the coils at the ends where they turn so that the oil can reach them on both sides and by providing circulation slots between the coils.

The radiation of heat from the case is facilitated by vertically corrugated surfaces which may be so designed as to greatly increase the radiating surface without increasing the cubic contents of the case.

Regulation. — The regulation of a transformer is dependent upon its ohmic resistance and its inductive reactance. Fortunately the size of the conductor required to keep the rise of temperature within safe limits is sufficient to keep the ohmic drop in the transformer down to a point which is satisfactory for general purposes. The fall of pressure in the transformer is fixed by the same principles which govern an alternating-current circuit. The resultant of the ohmic and inductive drops is the impedance drop, or $Z = \sqrt{R^2 + X^2}$, when Z is impedance drop, R is ohmic drop and X is inductive drop.

The impedance drop is, however, not the actual regulation of the transformer except at that power factor which is the same as the ratio of R to Z.

To determine the regulation at any power factor, the ohmic and reactance drops must be applied to the Mershon diagram. (See Chapter XVI.)

The reactance drop cannot be calculated directly, but may be determined by test as follows: With the secondary terminals of the transformer short-circuited through an ammeter the pressure on the primary terminals is brought up

until full-load current passes through the secondary ammeter. The pressure required to do this is the impedance drop. The resistance drop of primary and secondary is found by passing direct current through them and observing the voltage drop. The inductive drop is then found from the above formula $X = \sqrt{Z^2 - R^2}$.

Coil Insulation. — The insulation of the coils of a transformer from each other and from the case is of supreme importance. In transmission work large amounts of power are dependent upon the reliability of the transformer, while in distribution work not only the central station service but the lives of consumers and the general public are dependent upon it to a large extent.

The conductors are double cotton covered, to separate the adjacent turns, while the layers are separated by a proper thickness of varnished cambric, sheet mica or other insulating material. The completed coil is wrapped with linen tape covering the cotton braid, and impregnated with heated insulating compounds which drive off any remaining traces of moisture.

The primary and secondary coils being placed in close proximity are separated from each other by mica and hard wood or fiber so as to provide an oil-filled gap between the coils. The coils are likewise separated from the core by sheets of mica and other material. The cylindrical type of coils used in core-type construction and in the improved shell type are easily protected by layers of mica, and are therefore the most reliable form of coil for distribution purposes. Forms which require the protection of sharp corners are more difficult to insulate safely. Mica is not affected by heat or moisture and therefore forms the best insulating material where it can be applied effectively in sheets.

After being assembled on the core, the whole is impregnated

with insulating compound by immersion in heated tanks under a vacuum. This eliminates all traces of moisture and entrained air from the coils.

Case. — Distribution transformers are commonly provided with rugged cast-iron or sheet-steel cases adapted to stand exposure to the weather and to the rough handling incident to installation and removal. They must be oil-tight, as leakage

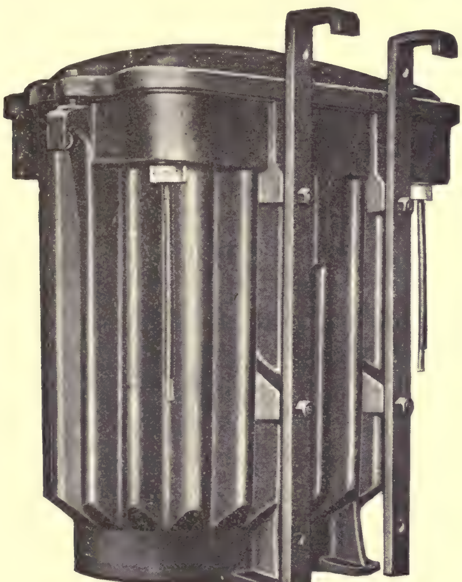


Fig. 58. Line Transformer Hangers.

is likely to result in claims for damages from property owners as well as very unsightly equipment. The cover is made removable for convenience in filling with oil and in changing the primary coil connections from series to multiple. Lugs are provided on the case to fit wrought-iron hangers by which they may be conveniently hung on a cross-arm, as shown in Fig. 58.

Polarity. — It is customary for each manufacturer, in bringing out the leads of distribution transformers, to follow a method of connecting coils on primary and secondary sides such that units may be coupled in parallel by following a symmetrical plan of connections without testing for polarity every time. The practice of manufacturers is not uniform however, and it is therefore necessary to test for polarity before putting transformers of different makes in parallel.

Connection Boards and Terminals. — The existence of old types of distributing systems operating at 1100 volts made it standard practice to provide a primary connection board in standard transformers so that they can be used interchangeably on 1100 or 2200 volts, by merely shifting the connecting strips from one position to another.

The tendency for these connection boards to become coated with dirt, thus forming a leakage path across the porcelain block, led to the practice followed by some manufacturers of placing the connection block below the oil level. Later this practice was found further justified by the fact that when terminal boards are submerged, there is a considerably reduced number of outages, due to blowing of primary fuses during lightning storms, and in stormy weather generally.

As a result of this it has become the practice of some of the companies having large numbers of transformers, which operate at 2200 volts (approximately) to have the primary connection board left out entirely in purchasing transformers and in repairing those damaged. In some cases, the blocks of all transformers returned to stock, which were not submerged, have been removed, thus gradually clearing up the entire installation. In the City of Chicago, this practice has resulted in a reduction of approximately 50 per cent in the number of primary fuses blown during lightning

storms and a substantial saving in the repair of coils and primary terminals damaged during such storms.

Efficiency. — The physical laws governing the magnetic characteristics of a transformer having an iron core are fortunately such that the relative amount of copper required is small, and the losses in the copper windings are not as great as they are in a generator or synchronous converter. The lack of moving parts further tends to make the transformer a most efficient piece of electrical apparatus.

The efficiency of a transformer which is used in transmission work is of most importance at the time of full load since it usually carries its load several hours per day, and its iron losses are a small part of its converted output. It is important, therefore, that its copper losses be low and its full-load efficiency as high as possible. In a distribution transformer supplying its full lighting load but two to four hours per day, the full-load efficiency is less important, while the iron loss which goes on 24 hours may become a considerable percentage of the daily output of the unit.

For instance, a 5-kw. transformer which carries full load 4 hours a day delivers 20 kilowatt hours per day, and has a copper loss of about 100 watts at full load, while the iron loss is about 45 watts. The copper loss per day is about 400 watt hours, while the iron loss is $24 \times 45 = 1080$ watt hours. The total loss being 1.45 kilowatt hours, the all-day efficiency is $\frac{20}{21.45} = 93.2$ per cent, while that at full load is $\frac{5000}{5145} = 97.1$ per cent. It is apparent that the all-day efficiency varies with the load factor or hours' use of the maximum load. The efficiency at various hours use for several sizes of transformers is shown in the curves in Fig. 59. It is evident from these curves that a system in which there are a considerable number of 1-kw. transformers will have a lower all-day

efficiency than one in which the same amount of load is supplied by 5-kw. transformers. The average size of transformers should therefore be kept as large as consistent with a reasonable investment in secondary mains.

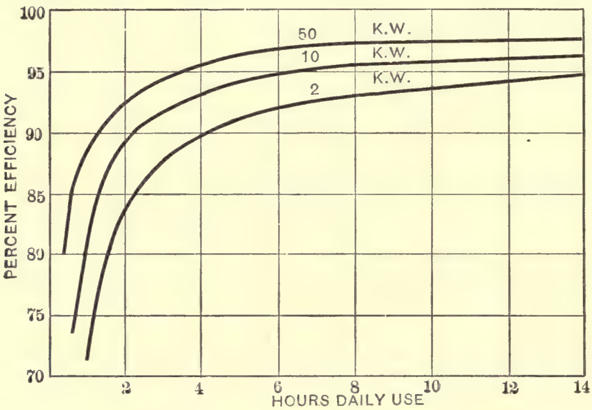


Fig. 59. All-day Efficiency of Transformers.

The average values of efficiency, copper loss, iron loss and regulation of distribution transformers of the improved shell type made by the leading American manufacturers are shown in the following table:

Kv-a.	Watts loss.		Per cent efficiency, full load.	Per cent regulation.		Per cent leakage current.
	Core.	Copper at 125° F.		100 per cent P.F.	80 per cent P.F.	
1	20	26	95.8	2.61	3.18	5.5
1½	25	37	96.2	2.47	3.10	4.0
2	30	46	96.5	2.33	3.00	3.6
3	34	70	96.8	2.36	3.01	3.0
4	40	82	97.2	2.08	3.12	2.5
5	45	102	97.3	2.08	2.10	2.3
7½	62	137	97.6	1.84	2.93	2.2
10	80	163	97.8	1.66	2.85	1.9
15	105	233	97.9	1.58	2.80	1.6
20	131	295	98.0	1.52	2.96	1.5
25	147	351	98.2	1.47	2.90	1.3
30	163	411	98.2	1.46	2.90	1.2
40	205	476	98.3	1.30	2.80	1.2
50	240	605	98.4	1.20	2.70	1.0

The copper loss and regulation figures in the above table are based on a temperature of 125 degrees F.

Three-phase Units. — In three-phase systems the possibility of saving a part of the core material and reducing the cubic feet occupied has led to the adoption of three-phase units in some kinds of work.

In the design of the core of three-phase units some saving in the weight of core metal is possible when the middle phase is connected in reversed order so that the magnetic fluxes of the adjacent phases do not combine in the usual 120 degrees relation but at 60 degrees apart.

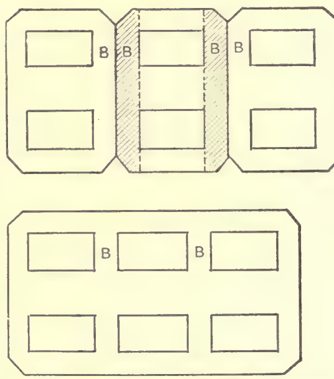


Fig. 60. Single and Three-phase Cores Shell Type.

For instance, the shell type unit, as shown in Fig. 60, may be designed with the same cross-section at *B* as each of the three single-phase units has at the points *B*, thus saving the shaded portion of the middle single-phase core.

In underground work the saving in space is of value in a manhole, but the shape of the three-phase unit is such that it cannot be installed or removed unless a special size manhole cover is used.

The three-phase unit has not, therefore, been generally used in distribution work, except where local conditions make it compulsory.

The three-phase unit as worked out in the shell type with air-blast cooling is shown in Fig. 61. This unit effects a saving in floor space and in first cost which has made it standard for synchronous converter work. In the core-type unit

Fig. 61. Three-phase Air-cooled Transformer.

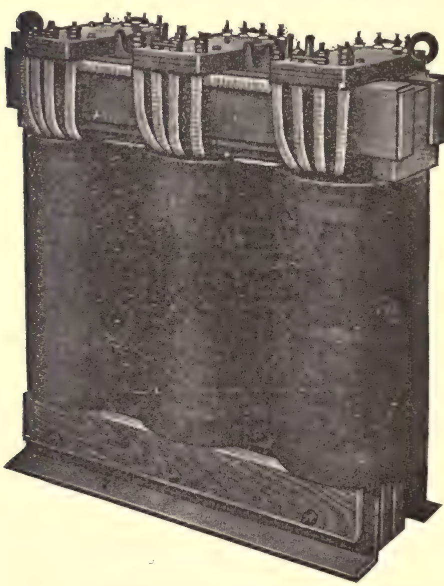


Fig. 62. Three-phase Oil-cooled Transformer.

illustrated in Fig. 62 the cooling is effected by oil, and this type is used in distribution work or in situations where attendance is not continuous. It is not usual to use a three-phase unit smaller than 15 kw. Having the three phases contained in one case they are made in larger capacities than single-phase units, having been made as large as 14,000 kv-a. for use in transmission work.

For general distribution purposes the three-phase unit has some serious limitations. It puts the entire load furnished by the unit out of service if any trouble develops in either phase of the unit, and the expense of providing a substitute unit is necessarily greater.

Where transformers of all sizes must be kept on hand to take care of light and power service it is more flexible to have single-phase units which are available for either light or power than to attempt to carry a line of single-phase units for lighting and three-phase units for power.

CHAPTER VI.

SECONDARY DISTRIBUTION.

Historical. — In the early stages of the introduction of alternating-current systems the use of 55-volt secondary circuits was adopted in some systems because of the more rugged character of incandescent lamps of these voltages. Such voltage could be used in alternating-current systems because of the possibility of locating transformers close to the customer's premises. However, it was not possible to supply more consumers from one transformer than could be reached from the pole on which the transformer was placed without an excessive use of copper. The result was a system in which a large number of small transformers were required. These consumed an excessive amount of energy in their cores and required the operation of extra generating capacity at times to supply their large leakage currents.

As these distributing systems attained such size that these items became an appreciable expense, a remedy was sought. The higher voltage lamp having been improved, 110-volt secondaries were introduced and the 55-volt consumers were gradually changed over to 110 volts. The use of the higher voltage increased the range of distribution so that a single 110-volt transformer was installed to replace several 55-volt transformers, with a saving in the amount of capacity required and a very great reduction in the core losses and leakage currents.

Later the availability of the Edison three-wire system for general secondary distribution increased the range of such lines by permitting the use of 110-220 volt mains, with 110-volt lamps.

At this voltage, distribution may be economically made from transformers spaced 600 to 1000 feet apart. This greatly increases the number of consumers which can be supplied from a single unit, and permits a great saving in investment as well as in iron losses since the larger kilowatt capacity in a single unit costs less than the same capacity in several smaller units and requires much less energy to supply the iron losses. For instance, in replacing five 1-kw. units, with one 5-kw., there is a saving of about 50 per cent in investment and iron losses.

Furthermore the diversity of habits of use of electricity of a large number of consumers is such that the maximum demand on a transformer which covers 1000 feet of line is much less than would be the sum of the maxima of several units covering the same consumers. The advantage thus gained from what is known as the diversity factor often permits a saving of 40 to 60 per cent in the investment in transformers as compared with house-to-house transformers.

The three-wire 110–220-volt system is used for single-phase secondary distribution very generally in American cities, where there are a number of consumers grouped within economic range of a transformer. Two-wire distribution is used where consumers are few and scattered as in the early periods of development.

Periods of Development. — A system of secondary mains passes through three general periods of development in the growth of a city.

(1) A period in which scattered transformers supply isolated secondary mains not interconnected with other transformers.

(2) A period in which the mains from adjacent transformers grow together along principal thoroughfares where they may be connected to each other but intersecting few other secondary mains of importance.

(3) A final stage in which secondary mains are required generally and are therefore joined into a network.

The first period is that found in residence and other outlying territory not fully built up. When a new consumer is to be connected in such a territory the problem is — Shall a transformer be installed or the nearest secondary main extended to the premises? The installation of a transformer involves an investment and an operating expense, due to its core loss. The extension of the nearest secondary main involves an investment in conductors and perhaps an increase in the capacity of an existing transformer. The cost of the two alternative plans being ascertained, the one selected should be that which involves the least annual cost for interest, depreciation and operation.

Example. — For instance, assume that service is required for a new consumer, with a load of 1 kw., at a point where there is no secondary main available. Also, that if a separate transformer is installed the investment will be about $25, and if the nearest secondary main is extended the expenditure will amount to $40. How shall service be given?

If the primary line is available and a new 1-kw. transformer is installed, the investment of $25 will involve expense as follows:

15 per cent fixed charges on $25	$3.75
Core loss — 20 wts. × 8760 hrs. = 175 kw. hrs. at $0.01	1.75
Total	$5.50

If the secondary line is extended at an expense of $40 (exclusive of poles), the fixed charges at 10 per cent are $4 per year.

If the existing transformer has surplus capacity or if there is a considerable diversity factor between the new consumer's

load and the existing load so that its capacity is sufficient, the extension of the secondary from the existing transformer is the more economical procedure. But if 1 kw. capacity must be added to the existing transformer, this will add about \$10 to the investment and 10 watts to the core loss. The fixed charges are increased by \$1.50 and the energy loss by \$.87, making the total expense \$4.00 + \$1.50 + \$.87 = \$6.37, as compared with \$5.50 for the installation of a separate transformer. The new transformer would thus be preferable under this condition.

If the extension is being made at the end of the line where the primary does not extend beyond the last transformer, the extension of the secondary is usually preferable where small consumers are being added. This condition holds until distance becomes too great to give satisfactory service or the consumers become sufficiently numerous to warrant the installation of a transformer. In residential districts, it is possible at times to extend secondaries from 600 to 1000 feet in this manner.

There is little occasion in this period of development to connect secondary mains in multiple. Where the mains have been extended until they meet each other it is usually preferable not to interconnect them, as the blowing of the fuse of either transformer shifts the load to the other, and overloading it blows its fuse also; and transformers are so far apart that they cannot assist each other to any appreciable extent in case of an overload on either of them.

The second period of development is reached when consumers become so closely situated that it is necessary to provide a continuous secondary main along a thoroughfare. This condition is usually first met along business streets and boulevards, and results in a long secondary main fed at intervals by transformers but intersected by few other secondary mains of importance. When such a main has been

established the problem is to determine how far apart transformers should be located and what size of conductor should be used.

The density of the load varies in different parts of the street, and there are large blocks of load at particular points which make the problem a perplexing one at best. A general solution is usually not possible, owing to the widely varying local conditions. However, a determination may be made which will serve to indicate the approximate limits within which the most economical arrangement of transformers and wire will lie, and from which some general principles of value may be deduced, as follows.

Calculation of Secondary Mains. — Assuming that energy is distributed from an overhead three-wire 110–220-volt secondary main 6000 feet long in equal amounts at intervals of 100 feet, what is the best size of wire and distance between transformers? For a given load density, the supply of electricity may be distributed from several small transformers, with small wire and short spacings between units, or from fewer units with larger wire and longer spacings. The use of many units tends to increase the transformer investment and the core losses, and to decrease the investment in conductors while the use of fewer units has the opposite effect. It is possible to find a point where the sum of these conflicting influences is a minimum.

The figures given in detail in Table II are based on 2 per cent maximum voltage drop on the secondary main, with overhead lines, weatherproof wire at 15 cents per pound, energy at 1 cent a kw. hour, fixed charges on transformers at 15 per cent and on conductors at 10 per cent. The iron losses are assumed to go on through 8760 hours per year. With 50 kw. per 1000 feet, and No. 6 wire, the transformers must be 400 feet apart to keep the drop within 2 per cent.

TABLE II

25 Kw. per 1000 Feet

Distance between Trans., Ft.	Size Cond. B. & S. G.	Number of Transf.	Size of Transf., Kw.	15% on Trans.	Value Iron Loss	Underground		Overhead	
						10% on Cable	Total Annual Cost	10% on Wire	Total Annual Cost
300	6	20	7.5	$208	$117	$145	$470	$30	$355
400	6	15	10	190	105	145	440	30	325
600	6	10	15	177	90	145	412	30	297
800	3	7.5	20	165	85	190	440	56	306
1000	1	6	25	158	75	282	515	88	321

50 Kw. per 1000 Feet

Distance between Transf., Ft.	Size Cond. B. & S. G.	Number of Transf.	Size of Transf., Kw.	15% on Trans.	Value Iron Loss	Underground		Overhead	
						10% on Cable	Total Annual Cost	10% on Wire	Total Annual Cost
300	6	20	15	$355	$180	$145	$680	$30	$565
400	6	15	20	330	165	145	640	30	525
600	3	10	30	300	145	190	635	56	501
800	1	7.5	40	285	137	290	712	88	510
1000	2–0	6	50	275	130	380	785	140	545

100 Kw. per 1000 Feet

Distance between Trans., Ft.	Size Cond. B. & S. G.	Number of Transf.	Size of Transf., Kw.	15% on Transf.	Value Iron Loss	Underground		Overhead	
						10% on Cable	Total Annual Cost	10% on Wire	Total Annual Cost
300	6	20	30	$603	$290	$145	$1038	$30	$923
400	3	15	40	573	272	190	1035	56	901
600	0	10	60	500	262	345	1092	190	872
800	4–0	7.5	80	425	250	510	1175	220	890
1000	300	6	100	374	231	650	1255	330	935

Fifteen units of 20 kw. each are required for the assumed length of 6000 feet. Their iron loss at 131 watts is 1965 watts, and the annual loss is 1965 × 8760 = 17,200 kw. hours. At 1 cent this will cost $172 per year. The value of fifteen 20-kw. transformers is about $2200 and 15 per cent of this is

$330. The value of 18,000 feet of No. 6 weatherproof wire is about $300 and 10 per cent ot this is $30. The total annual cost is therefore $172 + 330 + 30 = \$532$. In a similar way the calculations have been carried for No. 3 with t n 30-kw. and for other spacings and sizes of conductor.

These calculations, as made for load densities of 25 kw. and 100 kw. per 1000 feet of line on the Edison three-wire system with neutral full size, are also shown in the accompanying table.

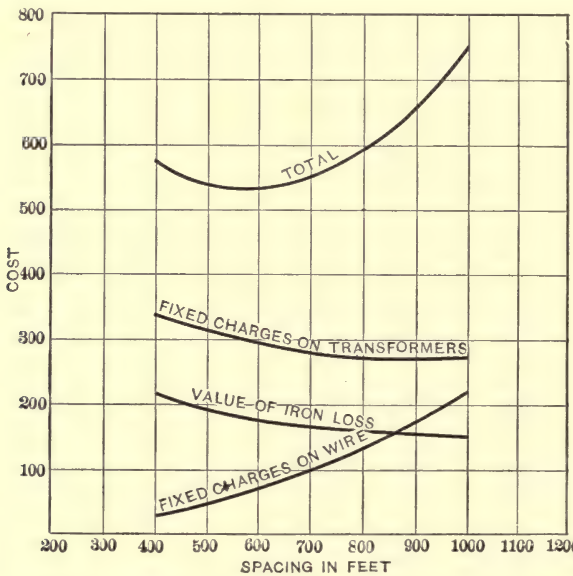


Fig. 63. Elements of Annual Cost, Secondary Main.

The variation of the elements of cost as the spacing between transformers and size of wire is increased is illustrated by the curves in Fig. 63, which are based upon the values obtained in the calculations made for a load density of 50 kw. per 1000 feet, with overhead lines. It is apparent from the curve of total cost that the minimum is found with a spacing of 600 feet between transformers.

The curves of total cost at densities of 25, 50 and 100 kw. per 1000 feet are shown in Fig. 64. It will be seen from these curves and the table of figures that with overhead lines, under the conditions assumed, the most economical spacing

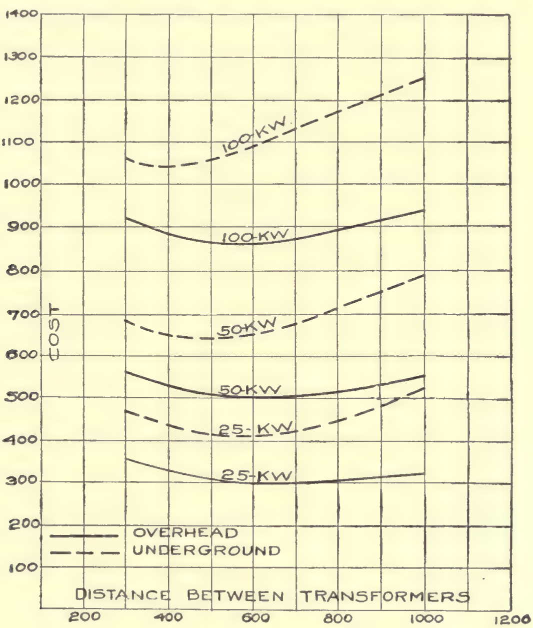


Fig. 64. Economical Transformer Spacing.

of transformers is from 500 to 600 feet apart, at all load densities from 25 to 100 kw. per 1000 feet. Where energy may be charged at less than 1 cent per kw. hour, or with water power, the decreased value of core loss tends to permit the use of shorter spacings and a smaller size of wire.

The calculation for underground lines is included in Table II and is also shown graphically in Fig. 64. The most important difference between these figures and those for overhead lines is in the cost of conductors. The figures are based on single-conductor lead-sheathed paper-insulated cables

and copper at 15 cents per pound. The absolute values of annual cost are from 20 to 25 per cent higher than with overhead lines, but the spacing for the minimum value is not materially changed, it being about 500 feet for each load density. The fact that the best spacing proves to be about 500 feet is a fortunate one in many cities where this is the approximate length of a city block. The location of transformers at intersections is especially desirable where the lines are on streets, as it permits of the supply of electricity in four directions from one unit.

The flatness of the curve of total cost allows considerable flexibility in spacing, and it is generally preferable to use few transformers with larger sizes of conductor, so as to reduce the number of units to a minimum. The curves indicate that this can be done if desired without seriously affecting the economy. Furthermore, it is usually desirable in building extensive secondary mains to anticipate an increase in load, by erecting a larger conductor than is required for immediate needs. The size of transformers may then be gradually increased as the load increases.

The entire foregoing discussion is based on an assumption that the load is evenly distributed along the line throughout its length.

However, in practice, it is more often the case that certain portions of a secondary main are heavily loaded, while others carry a more scattered load owing to differences in the character of the neighborhoods which it serves. At occasional intervals department stores, churches or other large consumers of electricity throw heavy loads upon the line.

It is therefore necessary to locate transformers near to such large consumers' premises and to design the main between them to carry the scattered consumers whose load is distributed between. An extended secondary main may thus be made up of different sizes of wire in different parts with

transformers having various spacings, depending upon the load density in the vicinity.

However, the design of those portions of a secondary main which serve the smaller consumers distributed along its route may be based upon the general theory outlined in the foregoing.

Networks. — The network is the last step in the development of a system of secondary mains. The gradual extension of mains on all intersecting streets results in a system of lines which is interconnected at intersecting points and thus becomes a network.

The use of direct current Edison networks in most of the larger American cities has prevented the development of extensive alternating current secondary networks.

The development of alternating current distribution by interconnected secondary main systems has thus been limited to the medium sized cities where the loads to be distributed in the central business portions range from 500 to 2500 kw.

In such districts it is desirable to have a single system for the general light and power service, as the use of a separate set of mains for power service results in a considerable duplication of investment, in the conductor equipment and in the absorption of valuable pole and conduit space which is required for the power mains.

The direct current Edison system is the only one which fully meets this requirement, as it can take on power in any amount required, with the lighting. The interference of th lighting service caused by alternating current motors, due to larger starting currents and low power factor, makes it necessary to maintain separate transformers for large motor installations and to restrict the sizes of motors which can be satisfactorily carried from the lighting mains. It is found practical to put somewhat larger motors on a three-

phase secondary main than on single-phase, and where three-phase distribution is employed for the general system, a three-phase secondary network is often employed in the central business district where there is no direct current system.

A network of secondary mains is usually supplied by transformers distributed about the system in proportion to the load served.

The transformers are naturally placed at intersections whence they may distribute energy in four directions with best use of conductor capacity.

The size of secondary mains is determined chiefly by considerations of current carrying capacity as the distance between transformers is not great, being usually from 450 to 600 feet, depending upon the lengths of the blocks.

It is usual to provide special transformer installations in, or immediately adjacent to the premises of consumers having loads of 50 kw. or more, such as theaters and department stores.

The arrangement of a network served by transformers at street intersections, is illustrated in Fig. 65.

The nature of the locality is often such that underground construction is required where a network exists. This necessitates manholes of ample size for transformers and such junction boxes as are necessary for the proper operation of the system. The space required is sometimes difficult to secure on account of gas and water pipes, car tracks and other underground systems. It is not desirable to go below such obstructions, as the manhole should not be below the sewer level.

Where the load densities are such that transformers of 50 kw. and upward are required at the intersections, the problem of securing sufficient space for manholes of suitable size becomes increasingly difficult. In some cities, it is found

practical to build vaults under the sidewalks, thus avoiding the piping systems in the streets.

In cases where there are alley lines intersecting secondary lines on streets, the manholes are placed at the alleys, thus

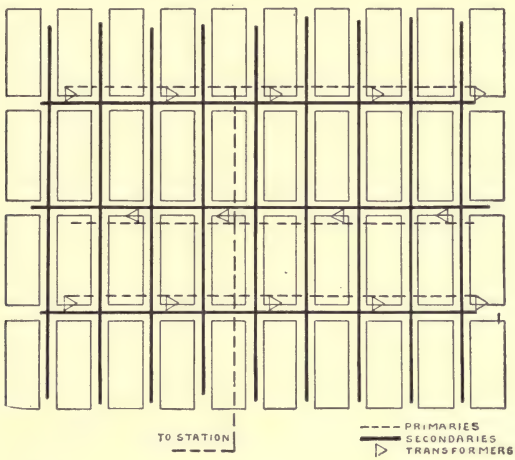


Fig. 65. Alternating-Current Secondary Network.

avoiding the congestion of underground structures at street intersections.

A further limitation of the size of transformer vaults in streets is found in the requirements for ventilation and heat dissipation. When manholes are in the street, ventilating facilities which will be adequate for large transformers are difficult to arrange and it may not be possible to prevent excessive temperatures at certain hours of the day.

These various difficulties have been sufficient in some cases to result in a decision to avoid the use of transformers in streets by distributing energy from low tension feeders and mains supplied by a transformer substation, centrally located.

This arrangement permits a considerable saving in transformer investment and iron losses, as the diversity factor

reduces the capacity required and the economy of larger units is realized.

This saving is, however, largely offset by the greater cost of low tension feeder cables.

Mains for Power Service. — The installation of separate transformers for power load necessitates separate secondary systems for power consumers whose premises are in the same vicinity. The design of such mains is governed by the same principles that control the arrangement of lighting mains, except that it is permissible to allow the secondary line drop to be 5 per cent or more instead of 2 to 3 per cent required for satisfactory incandescent lighting. This permits power secondary mains to be extended to about twice the permissible range for incandescent lighting. In manufacturing districts the power load usually exceeds the lighting, and duplicate secondary systems for light and power are often found. In residence and mercantile districts the reverse is the case, and the heavy lighting secondary system is capable of absorbing some miscellaneous power without seriously affecting the lighting service.

However, this is not desirable with the types of power which are intermittently used such as coffee mills, meat grinders and other small apparatus which is used in retail stores.

The starting currents of these motors when wound for 110 volts range from 20 to 30 amperes or 10 to 15 times normal running. As the supply circuits are designed for the normal running current, there is a pronounced drop in pressure at the instant they are switched on which produces flickering of lights. When the starting is frequent, this results in serious interference with lighting service, particularly in cases where retail stores are in or near residence districts. Relief can be secured in many cases by requiring motors which start fre-

quently to be wound for 220 volts. In other cases a separate transformer is required.

Polyphase Systems. — In two-phase systems it is usual to operate the lighting single-phase, as this is the simplest and most economical plan. The two-phase power service is supplied from separate transformers. In a few large two-phase systems where light and power are carried on the same underground secondary systems, two extra conductors have been provided from the other phase for two-phase power consumers, making a five-wire secondary system and five-wire services where light and power are served in the same building.

In three-phase systems several methods of carrying mixed light and power load are in use. The most common consists of star-connected transformers supplying a four-wire main operated at about 115 volts from phase to neutral and 200 volts across phase wires. Lights are balanced as nearly as possible on the three phases. The smallest lighting services are two-wire, while larger ones are made three-wire, and connected to two phases and neutral and those of about 5 kw. or more are connected on three phases. Four-wire service is required for the larger users and in all cases where both light and power is to be served in the same building. The disadvantages of this system are the difficulty of maintaining a proper balance and the necessity of installing three transformers at each point where the secondary main is fed.

In another method, which is illustrated in Fig. 66, all the lighting is carried on one phase by means of a three-wire Edison secondary. Small power may then be served by the installation of one additional smaller transformer and a fourth secondary wire. Larger power may require two power transformers in addition to the lighting transformer. The lighting in this system is easier to keep balanced, and since it is all on one phase the higher diversity factor requires less transformer

capacity for lighting purposes. This reduces transformer investment and core loss materially as compared with the star-connected secondary, as the average size of the units is larger and the total capacity required is somewhat less.

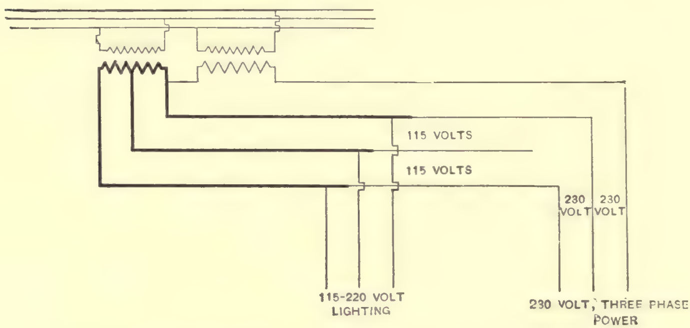


Fig. 66. Lighting on One Phase of Three-phase Secondary.

Another advantage of carrying all lighting on one phase is that the effect of the starting current of motors is less noticeable on the lighting supplied by the large unit than it is where the starting current is drawn from three smaller transformers, each of which carries lighting load. It is therefore possible with this system to carry somewhat larger power loads on the same secondary main with the lighting than in the star-connected system under the same conditions.

When a network has been developed, this system cannot be interconnected with other secondary mains except those which are fed frcm the same primary phase. As the extent of the network increases this becomes undesirable and the objections to the star-connected system become less important. The four secondary conductors may then be changed over to a star-connected system and the network may be interconnected throughout.

The use of combined light and power secondary mains becomes desirable in an underground system as soon as there

is a sufficient number of power consumers to require a general system of power secondaries in any locality.

The expense of extra ducts and separate cables for separate power secondaries is excessive, and it is desirable to combine light and power secondaries into one system at an earlier stage of development than in the case of overhead lines.

Determination of Transformer Capacity. — The selection of the proper size of transformers for the supply of various classes of consumers is important since excess capacity involves idle investment and unnecessary core losses. The size of transformer units should therefore be kept as low as possible, consistent with preservation of the apparatus and good regulation.

Most electric light and power consumers do not use their entire connected load at any one time. There are always some lamps which are not in use at times when the principal part of the lighting is on, and in power installations the maximum load is usually less than the rated capacity of the motors.

Where a number of consumers are grouped on one transformer the maximum demands of the various consumers do not occur simultaneously and the resultant maximum demand is less than the sum of the individual demand. Measurements of demand may be made by means of an ammeter or by a Wright demand indicator. The use of the demand indicator is preferable as it may be left in circuit throughout any desired period and the maximum for the entire period thus determined. Certain demand factors may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These factors may then be applied with reasonable accuracy to the selection of transformers for new consumers.

In store lighting the maximum demand for window lighting, signs and other display lighting is from 90 to 100 per cent

of the load. The demand factor on interior store lighting is 50 to 70 per cent.

In residences having 40 or more lamps installed the average maximum demand of a group is 15 to 20 per cent of the connected load. Individual residences may have occasional maxima of 40 to 60 per cent, for which some allowance should be made in selecting transformer capacity. The size of the transformer should be such that it will safely carry the occasional high demand of the largest individual consumer together with the average demand of the other consumers on the transformer.

TABLE OF DEMAND FACTORS IN LIGHTING SERVICE

Description of load	Number of customers	Kilowatts connected	Kilowatts demand	Demand factor (per cent)
Residence	137	84.7	18.9	22.3
Residence	68	126.6	15.75	12.4
Residence (119 kw.; stores 11 kw.)	196	129.5	28.85	22.3
Residence (1 customer, 7.5 kw.)	5	10.3	9.45	92.0
Residence 70 kw.; stores 7 kw.	77	77.0	21.0	27.3
Residence (59.7 kw.; hotel 48 kw.)	66	107.7	26.25	24.3
Residence (1 30-amp. rectifier)	121	183.5	30.5	16.6
Residence	34	47.5	10.5	22.2
Residence (2 30-amp. rectifiers)	19	79.2	15.7	19.8
Residence (1 30-amp. rectifier)	21	67.7	13.6	20.2
Residence (1 30-amp. rectifier)	21	54.1	13.1	24.3
Residence	47	68.7	8.4	12.2
Residence	144	129.95	22.6	17.4
Residence (4 30-amp. rectifiers)	43	59.0	26.6	42.0
Residence	85	99.65	16.1	16.1
Residence	84	112.5	14.7	13.2
Residence, 20 kw.; Stores 15.7 (hotel 25 kw.)	38	60.7	27.3	45.0
Residence	99	59.0	8.4	14.2
Residence	89	100.45	13.7	13.6

Residences and apartments having connected loads of 30 lights or under make a demand of about 20 per cent of the connected load at the time of the daily maximum.

In general a higher factor must be used where there are but two or three consumers on a transformer than where there are

more, as the occasional maxima of individual consumers are a much larger percentage of the total.

In the case of churches and similar public buildings, capacity must be provided for the illumination of the largest room in the building together with the necessary hallways and corridors. This usually requires capacity for at least 60 to 75 per cent of the connected load.

In theater lighting the border and footlights of several colors are not used simultaneously and the stage and auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theater the factors may be from 70 to 100 per cent while in a large theater it is frequently as low as 50 per cent.

Where several classes of buildings are fed by one transformer the capacity must, of course, be determined by taking each class into consideration separately and thus arriving at an average demand factor for the whole.

The selection of transformers for power consumers is more difficult, as the maximum load may vary greatly from day to day or from month to month. The maximum load should be estimated where possible from the nature of the work done rather than from the motor rating, as motors are frequently chosen with reserve capacity. Elevator and crane motors require transformers of 100 to 125 per cent of their rated capacity unless there are several motors supplied by one unit. This is necessary in order to hold up the pressure in starting. The load of such equipments is so intermittent that heating is usually not a factor in determining the size of the transformer.

The figures in the following table were made up from several thousand installations of direct-current motors in Chicago, which were equipped with maximum demand meters. They may be considered as representative, as they embrace every kind of manufacturing work which is commonly supplied by central stations systems.

TABLE OF DEMAND FACTORS IN MOTOR SERVICE

Total installation in h.p.	Number of customers	Total h.p. connected	Average maximum h.p.	Ratio of maximum to conn. h.p.
1 motor,				
1 to 5	1177	2165	1862	86.1
6 to 10	124	1036	676	65.3
11 to 20	32	492	303	61.6
above 20	17	686	366	53.2
Total	1350	4379	3207	73.3
2 motors,				
1 to 5	177	412	285	69.1
6 to 10	51	387	261	67.4
11 to 20	30	438	288	65.9
above 20	6	203	74	36.5
Total	264	1440	908	63.0
3 to 5 motors,				
1 to 5	150	381	314	82.5
6 to 10	42	290	238	82.1
11 to 20	33	475	329	69.3
above 20	14	1245	657	52.7
Total	239	2391	1538	64.3
6 to 10 motors,				
1 to 5	42	121	80	66.0
6 to 10	21	157	98	62.4
11 to 20	10	155	98	63.1
above 20	19	931	417	44.7
Total	92	1364	693	50.8

Regulation of Transformers. — The regulation which will be secured with a given transformer may be calculated, if the impedance drop of the transformer is known. For instance, assume that a 10 kw. transformer wound for 2200–110 volts has an impedance drop of 80 volts or 3.6 per cent, also that the ohmic drop in the primary and secondary coils measured by means of direct current is 1.8 per cent or 40 volts, at full load. The reactance drop is

$$X = \sqrt{(80)^2 - (40)^2} = \sqrt{6400 - 1600} = 69 \text{ volts} = 3.1\%.$$

In Fig. 67 let OA be the impressed pressure on the primary at no load. AB is the ohmic drop in the transformer windings, which in this case is 40 volts. This is in opposition to the impressed e.m.f., and must therefore be added directly

to it in determining what pressure must be impressed on the transformer in order to deliver its rated secondary pressure at full load. *BC* represents the inductive drop of 69 volts which must be laid off at right angles to *AB*. The pressure necessary to secure 110 at the secondary at full load is therefore $OC = \sqrt{(2240)^2 + (69)^2} = 2241$ volts. With an incandescent lamp load of 100 per cent power factor the regulation of this transformer is $2241 - 2200 = 41$ volts or 1.8 per cent.

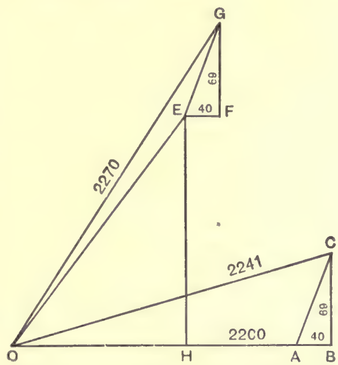


Fig. 67. Transformer Regulation, Inductive Load.

With a load of 10 kilovolt amperes at 70 per cent power factor the regulation is calculated thus:

In Fig. 67 the impressed pressure 2200 volts at no load is *OE*. This is opposed by the power-consuming component of the load $OH = .7 \times 2200 = 1540$ volts, and the wattless component $EH = .71 \times 2200 = 1562$ volts. The ohmic drop in the transformer $EF = 40$ volts and the inductive drop $FG = 69$ volts. The impressed pressure at the primary necessary to maintain 110 volts at the secondary of the transformer is therefore

$$OG = \sqrt{(OH + EF)^2 + (EH + FG)^2},$$
$$OG = \sqrt{(1580)^2 + (1631)^2} = 2270 \text{ volts.}$$

The drop at 70 per cent power factor is $2270 - 2200 = 70$ volts $= 3.2$ per cent. At 100 per cent overload this would be 6.4 per cent. With a motor taking two or three times full-load current at a power factor of 70 per cent or less at starting, it is evident that incandescent lights supplied by the same transformer will flicker whenever the motor is started and will burn at reduced candle power while the motor is running,

unless the motor load is so small compared with the lighting that the starting current is less than the full-load current of the transformer.

With a load consisting of arc lamps, the power factor of which is 75 to 80 per cent, the drop at full load would be about 3.0 per cent. This would be considered too much for satisfactory incandescent lighting in many cases, and if so it would be necessary to set a separate transformer for the arc lamps. When combined with an equal amount of incandescent lighting, the resulting power factor at the transformer is increased to about 95 per cent and the regulation of the transformer is within proper limits for satisfactory lighting.

The table on page 126 shows some of the characteristics of line transformers of the sizes commonly used, which will be of use in making calculations. Improvement has been made by reducing the reactance drop in the smaller sizes of transformers in recent years.

CHAPTER VII.

SPECIAL SCHEMES OF TRANSFORMATION.

The use of various distributing primary and secondary voltages and of single, two and three-phase systems gives rise to situations at times which require the use of various unusual schemes to fit these together with standard apparatus.

A breakdown in an industrial plant may make it necessary to get quick action in furnishing power from the central station system. Or conditions may arise when it becomes desirable to be able to render service to a consumer who has been securing his service from a different system.

Such situations cannot always be easily met since a change from the direct to alternating current, or other conditions which necessitate a change in motors, involve an expense which is likely to be very great.

However, there are situations which can be met with comparative ease, with standard apparatus and special connections. Some of the combinations of apparatus and connections which are most likely to be used as well as others which are not common, are presented herewith.

Transformer Connections. — The connections of standard line transformers are shown in Fig. 62 for convenient reference. These transformers are usually made with two primary and two secondary coils, which permits their use on 2200-volt circuits, as shown in Fig. 62 (*a*), or 1100 volt circuits, as in Fig. 62 (*b*). Similarly the secondary may be connected for 110 volts to supply lighting or power on the two-wire system,

as in Fig. 68 (*a*), or for lighting or power on the three-wire Edison system at 110–220 volts, as in Fig. 68 (*b*).

Some systems operating at approximately 2080 volts use a standard transformer having windings for 1040–2080 to 115–230 volts, making a ratio of approximately 9 or 18 to 1.

Primary connections may be changed from 2200 to 1100 volts by means of a connection block inside the transformer case.

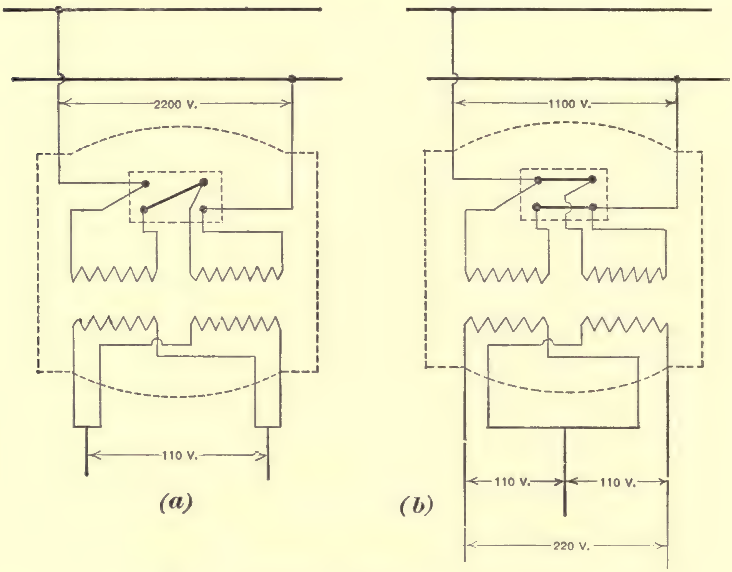


Fig. 68. Standard Transformer Connections.

The terminals of the secondary coils are brought outside the case in such proximity that they are readily put in parallel by joining the adjacent terminals. For 110–220-volt operation the two middle terminals are connected together, this forming the neutral of the three-wire system. Connection blocks are not used on the secondary side because of the large current-carrying capacity required.

The connections for three-phase three-wire and four-wire systems are shown in Fig. 63. The three-wire connection in

Fig. 69 (*c*) is familiarly known as the delta connection, because the triangle by which it is often represented resembles the Greek letter delta.

The four-wire connection in Fig. 69 (*d*) is produced by connecting all right-hand terminals to the phase wires and all left-hand terminals to the neutral, or *vice versa*. This con-

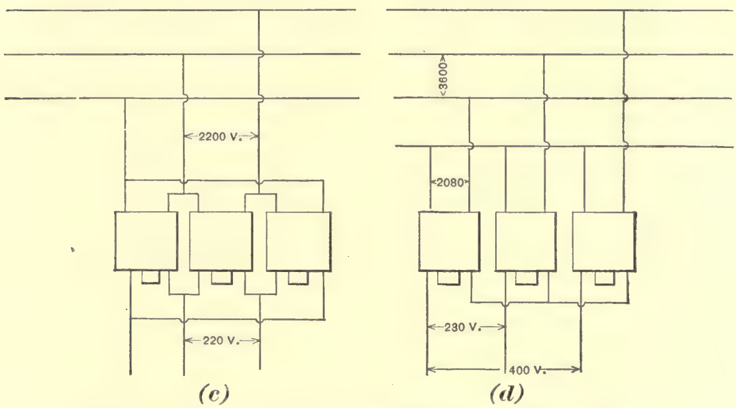


Fig. 69. Standard Three-phase Transformer Connections.

nection is called the Y connection because of its resemblance to that letter when represented in a polar diagram.

In the three-phase, three-wire delta connected distribution systems, it is customary to use a pressure of about 2200 volts, using standard 2200 volt transformers connected across the phase wires.

In Y connected four-wire distributing systems the pressure is operated at about 2200 volts between the neutral and each of the three outer or phase wires. This gives approximately 3800 volts between any two phase wires. Hence in order to use standard 2200 volt distributing transformers, the connection of transformers for lighting is made from either phase wire to the neutral conductor, and installations for three-phase power are Y connected on the primary side. The

neutral conductor is usually not connected to a Y connected power installation except with the open delta as explained later in this chapter.

The secondary connections may be made for delta three-wire operation or for Y operation with either three or four wires. Each of these schemes may be used on transformers supplied by either delta or Y connected primary. The connections shown in Fig. 69 (*c*) are from delta primary to delta secondary, but the Y connected secondary shown in Fig. 69 (*d*) may be used in (*c*) or *vice versa.*

The standard secondary voltages of 110–220 are commonly used for delta connection secondary, though 440 volts is not uncommon in large industrial plants where distances are considerable. The Y connected secondary is commonly operated at 110 volts from neutral to phase and this gives $110 \times 1.73 = 190$ volts between phases. Where the Y connected secondary is used for a mixed light and power load, it is usually operated at 120 to 130 volts in order to get 220 volts between phases for motor service. A four-wire secondary system of this sort is sometimes used in a commercial district and is referred to as a 120–210 volt or 115–200 volt four-wire system (as the case may be). Similarly 400 volt motor service may be given from 230 volt transformer by using the Y connection of secondaries. Where 440 volt service is required from 230 volt transformers, it may be secured by the use of 10 per cent boosters in the primary, as explained later in this chapter.

Booster Transformers. — Where it is necessary to raise or lower pressure when line drop is excessive, this may be accomplished in steps of 5 per cent or 10 per cent by a transformer used as a booster, that is, a transformer so connected that the secondary is in series with the primary main line. This raises the primary pressure by the amount of the secondary

voltage, thus boosting the pressure of the circuit, as shown in Fig. 70.

For instance on a long, single-phase 2080-volt lighting branch

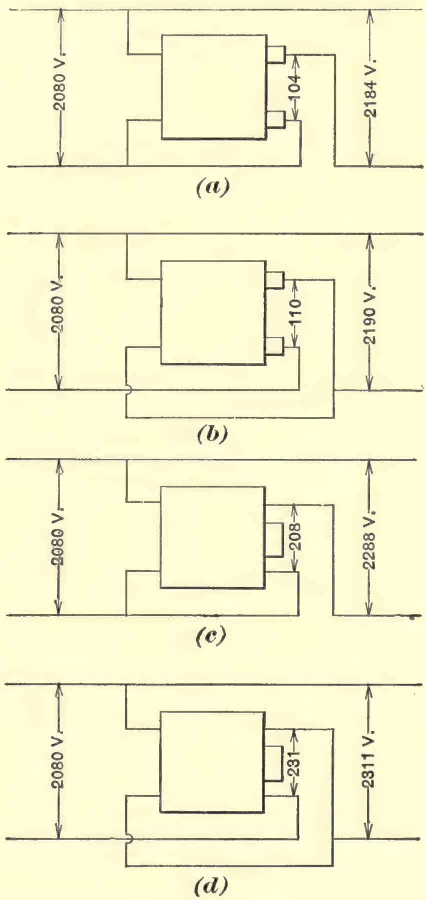


Fig. 70. Booster Transformer Connections.

which has so much load that the pressure drop is more than the normal regulation of the feeder will care for, a 110-volt transformer inserted in the line as a booster will raise the

primary pressure 110 volts. This raises the secondary pressure 5.5 volts on all the transformers beyond the booster.

This increase in pressure is independent of the load carried by the circuit and therefore the pressure is maintained at a point about 5 per cent above normal during the hours when the load is small. If 10 per cent or more is added to the line pressure by boosters it is therefore desirable to arrange the booster, if possible, so that it can be switched out during the period when the load is small. This may be done by using a separate transformer for each step of 5 per cent.

It is desirable to place boosters as near the source of supply as possible, since the booster adds 5 per cent or 10 per cent as the case may be, to the current drawn by the branch of the circuit in which it is connected, and this increases the line drop proportionately.

The size of the transformers used as a booster must be such that its secondary coils may safely carry the full-load current on the primary main. In general, if the transformer is to be used as a 5 per cent booster, it must have a capacity of at least 5 per cent of the maximum load on the main line, and if it is to boost 10 per cent, it must be able to carry 10 per cent of the load, etc.

With the secondary reversed the transformer becomes a choke, depressing the line pressure instead of raising it. This is a useful device in some schemes of connection, where less pressure is desired.

The proper connection of the secondary for booster or choke must usually be determined by trial for any given type of transformer, but once determined any transformer of the same type may be connected in a similar manner. The connections of Fig. 70 are those for the transformers of the principal makers.

The connections for a single phase booster are made as shown in Fig. 70 (*a*), the line pressure being raised from 2080 to 2184 volts, or 5 per cent. The connection in (*b*) is that

for an augmented booster, in which the line pressure is raised from 2080 to 2190, because the primary of the booster is connected across the line on the far side, and the booster is boosted as well as the line. This gives an increase of 5.5 per cent in the line pressure.

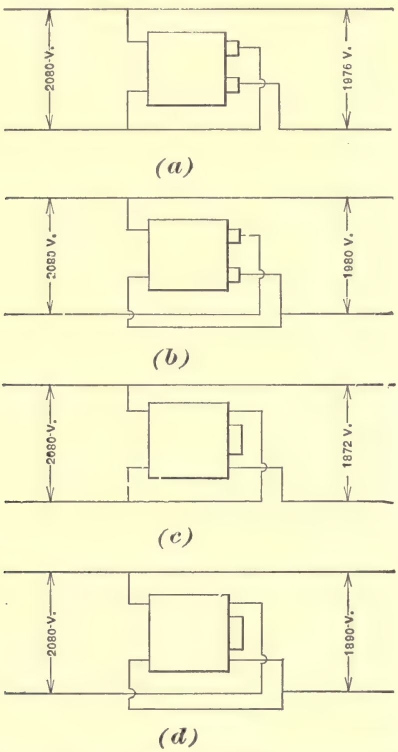


Fig. 71. Connections for Choking Transformers.

Fig. 70 (*c*) shows 10 per cent simple booster and (*d*) an augmented 11.1 per cent booster.

The corresponding connections for a 5 per cent choke are shown in Fig. 71 (*a*), a 4.75 per cent choke in (*b*), a 10 per cent choke in (*c*) and a 9.1 per cent choke in (*d*).

It should be noted that the transformers used in these illustrations have an interchangeable 10 or 20 to 1 ratio of transformation, and that these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2080 to 115–230 are used the amount of boost is increased about 10 per cent. Fig. 70 (*a*) becomes 5.5 per cent, (*b*) 6.05 per cent, (*c*) 11.1 per cent and (*d*) 12.2 per cent. Similarly the chokes in Fig. 71 (*a*) would be 5.5 per cent, (*b*) 5.24 per cent, (*c*) 11 per cent and (*d*) 10 per cent.

Booster Cut-outs. — There are certain precautions which should be observed in the installation of boosters, to protect them from injury. The booster secondary is in series with the line, and current is drawn through its primary windings in proportion to the load on the line. If the primary of the booster is opened while the secondary is carrying the line current the magnetization of the transformer is greatly increased and the booster acts as a series transformer. This causes a large increase of pressure in the booster, imposing upon its primary coils a high pressure, and the insulation of a 2200-volt transformer may be subjected to a potential of 10,000 to 20,000 volts or more, depending upon the load carried by the main circuit at the time.

If a fuse is used in the primary the blowing of the fuse creates this condition and the arc holds across the terminals of the block until it burns itself clear and is quite sure to break down the insulation of the primary coil.

The safest method of connecting or disconnecting a booster is to open the main line while putting it in or out of circuit. However, if the service cannot be interrupted, or if it is desired to switch the booster in or out periodically, this may be accomplished by the use of a series cut-out, connected as shown in Fig. 72.

The operation of the cut-out simultaneously opens the

primary and short-circuits the secondary of the booster. The switch must be of a type having a positive action, so that arcing will not damage its contacts at the moment the secondary is short-circuited. It must also have sufficient carry-

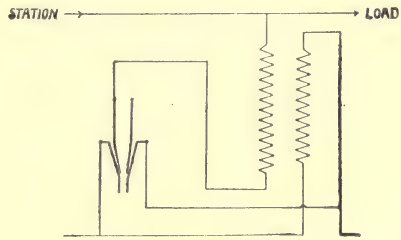


Fig. 72. Booster Cut-out.

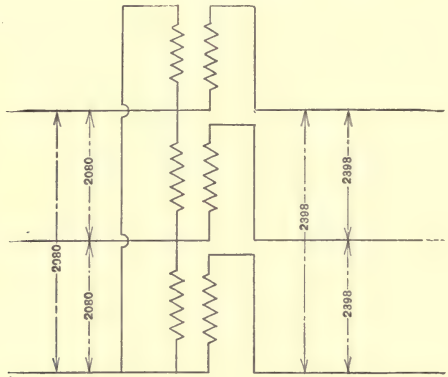
ing capacity to carry the main line current, and standard series arc cut-outs should not be used where the line current is likely to be over 20 to 25 amperes.

When the augmented booster is used the terminals of the primary winding of the transformer which goes to the cut-out should be connected to that terminal of the cut-out which is shown as not being in use in Fig. 72.

Boosters in Polyphase Systems. — The connections for boosters in a two-phase system are similar to those shown in Fig. 70 for the single-phase system. Where three-wire two-phase feeders are used the boosters are looped into the outer wires and the pressure is taken from the common wire.

The use of boosters in a delta-connected three-phase system is not so simple as is the single-phase application. The booster is looped into the line and pressure is taken for the primary coil from an adjoining phase wire, as in Fig. 73. The insertion of a booster on one phase affects the pressure on two phases, as shown diagrammatically in Fig. 74, which illustrates the effect of a 10 to 1 booster put into the "C" phase

only. When boosting, the pressure from A to C is raised 110 volts, while B to C is raised 208 volts, the pressure coil of the booster being connected from B to C.



(a)

Fig. 73. Three-phase, Three-wire Booster Connections.

The effect of a booster in each phase is seen in Fig. 74 in the larger dotted triangle, and the smallest triangle in the same figure shows the effect of a choke in each phase.

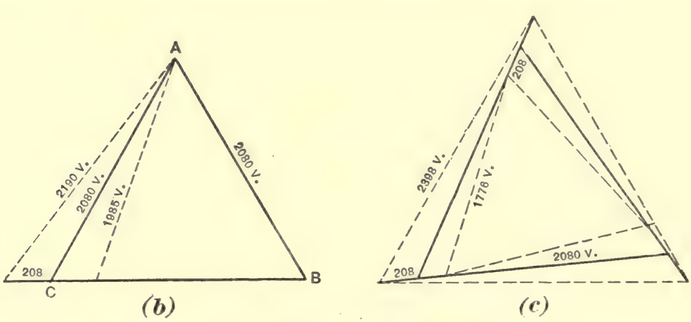


Fig. 74. Effect of Booster in Three-phase Circuit.

Three boosters are therefore required to keep conditions in balance, in a three-phase three-wire circuit.

The boosting or choking effect when various booster trans-

former ratios are used in one, two or three phases is expressed in percentages of the primary voltage in the following table:

BOOSTING.

Ratios.	10 to 1.			20 to 1.			9 to 1.			18 to 1.		
Booster in	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*
A phase....	10	0	5.3	5	0	2.65	11	0	5.8	5.5	0	2.9
A and B....	15.3	10	5.3	7.65	5	2.65	16.8	5.5	5.8	8.4	2.75	2.9
A, B and C..	15.3	15.3	15.3	7.65	7.65	7.65	16.8	16.8	16.8	8.4	8.4	8.4

CHOKING.

A phase....	10	0	4.6	5	0	2.3	11	0	5.06	5.5	0	2.53
A and B....	14.6	10	4.6	7.3	5	2.3	16.06	11	5.06	8.3	5.5	2.53
A, B and C..	14.6	14.6	14.6	7.3	7.3	7.3	16.06	16.06	16.06	8.03	8.03	8.03

In a Y connected four-wire three-phase system the boosters may be connected in such a way that the pressure is controlled in each phase independently of the others. The booster is put in series with the phase wire and the primary is connected from the same phase to the neutral. The connections are the same as for a single-phase circuit if each phase is considered as a separate circuit, the neutral being regarded as the opposite pole of all phases.

In cases where it may be desirable in an emergency to give 440 volt service by means of 230 volt, 9 to 1 transformers, this may be done by installing a 10 per cent booster in each phase. The secondary connection being made Y for normal operation at 230–400 volts, the pressure is raised to 440 volts by putting the 10 per cent boosters into the primary side of the main transformers. It is, of course, possible to do this in the same way with 10 to 1 transformers, if the system is normally operated at 2300 volts on primary distributing mains.

Booster schemes should, in general, be regarded as tentative remedies, rather than permanent schemes of operation. Their use is unavoidable at times in developing distribution systems in districts where consumers are widely scattered, and this is the field in which they are most frequently employed. They should be eliminated as soon as the density of the load reaches a point which justifies a sufficient number of feeders to make their use no longer necessary.

Auto-Transformers. — The introduction of incandescent lamps of high efficiency having characteristics which render

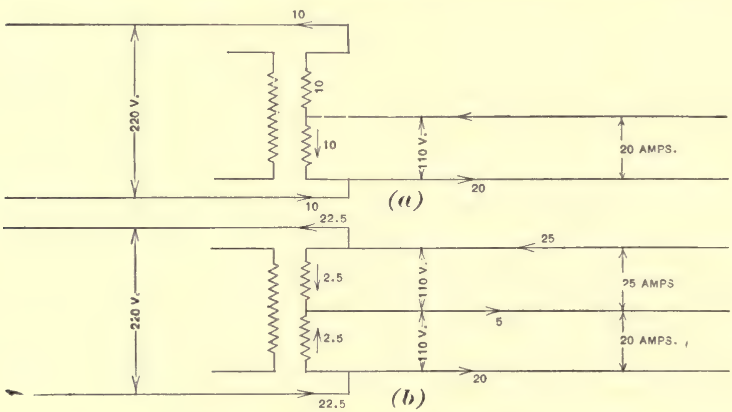


Fig. 75. Auto-transformer Connections.

them most durable at the lower voltages has greatly increased the field of application of the auto-transformer. It is desirable in plants using 220 volt and 440 volt systems to have available 110 volt circuits for lighting. Where the proportion of lighting service is small it is sometimes preferable to use a standard transformer as an auto-transformer.

The connections in Fig. 75 are those for two-wire 110-volt distribution on a 220-volt system, the load being assumed at 20 amperes. The distribution of current in the winding

is indicated by the figures and arrow heads. It will be seen that the transformer capacity required is equal to the load, when a standard transformer is used.

When the lighting is distributed on the three-wire 110–220 volt system, the transformer carries only the unbalance of current in the two sides of the system, as shown in Fig. 75(*b*). In this case the unbalance is 5 amperes. The transformer carries $2\frac{1}{2}$ amperes at 220 volts, and need be only large enough to carry the largest unbalance which is likely to occur. The primary terminals of the transformer are not used in either case and should be well insulated to guard against accident.

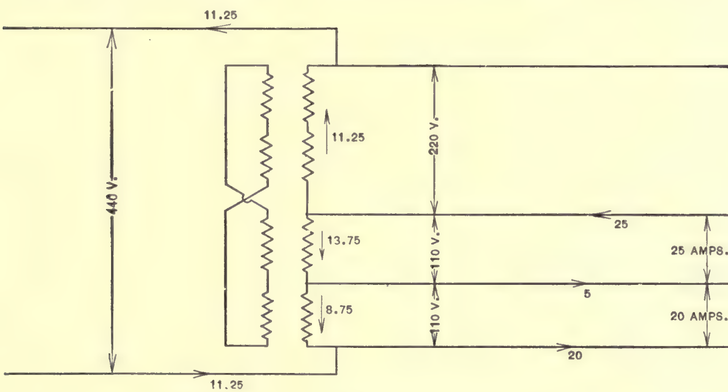


Fig. 76. 110–220 Volts from 440 Volts.

In a 440-volt plant, 110-volts lighting may be secured from standard transformers, as in Fig. 76. This requires the use of two transformers in series on the 220-volt side and in parallel on the primary side. It is important that the primaries be in parallel, as the other transformer acts as a choke if the primary terminals are left open, as in the case of a single transformer.

The lighting distribution in a 440-volt system is preferably accomplished by the three-wire 110–220 volt system, as this only requires transformers of capacity equal to the load, while

two-wire 110-volt distribution requires that the transformer on the side on which the lights are connected have a capacity of 1.5 times the load, and the other one must carry half the load, making the total capacity twice the load.

It would be possible, of course, to run a five-wire system or two three-wire systems, and so reduce the transformer capacity to that of the unbalanced load, but this would not

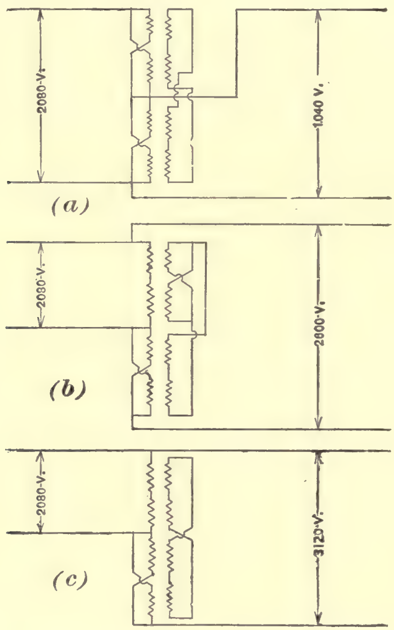


Fig. 77. 1040, 2600, and 3120 Volts from 2080 Volts.

often justify the increased complication of the wiring which would be occasioned by such an arrangement.

Combinations may be made on the primary side of standard transformers in a manner similar to those above outlined for the purpose of securing intermediate or higher voltages from the supply system. 1040, 2600 or 3120 volts can be gotten from a 2080-volt system by the use of two transformers

in series on the primary and in multiple on the secondary. These connections are shown in Fig. 77 (*a*), (*b*) and (*c*), respectively.

Various other combinations are possible by the use of more than two transformers, by which higher primary or lower secondary and other intermediate voltages may be derived.

Applications to Special Cases. — One application of the foregoing general principles serves to illustrate the value which such devices may have under certain conditions.

An installation consisting of a 300-kw. 2080-volt three-phase motor was to be supplied with energy from a four-wire Y-connected system operated at about 2160 volts between phase and neutral, or 3740 between phases.

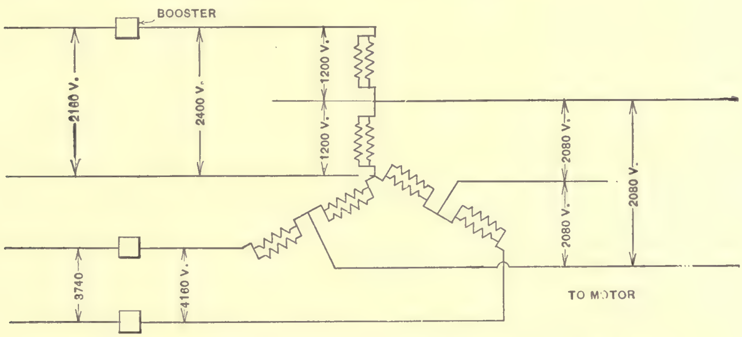


Fig. 78. 2080 Volts from Four-wire Three-phase System.

The only transformers available for the purpose were six 50-kw. core-type transformers, with primary coils wound for 1040 or 2080, and secondary for 115 or 230 volts. By connecting these transformers for 1040 volts on the primary and putting two in series from each phase to neutral, with secondaries in parallel, it was possible to take the motor circuit off at half the line pressure. The line pressure being but 3740, the additional amount required to get 4160 was secured by the use of a 9 to 1 booster in each phase.

The connections are shown in Fig. 78.

Three-phase from Two Transformers. — The cost of transformers for small three-phase power service makes desirable in many cases the use of schemes of connection by which three-phase secondary service may be derived from two transformers. Two schemes of connections are possible for this

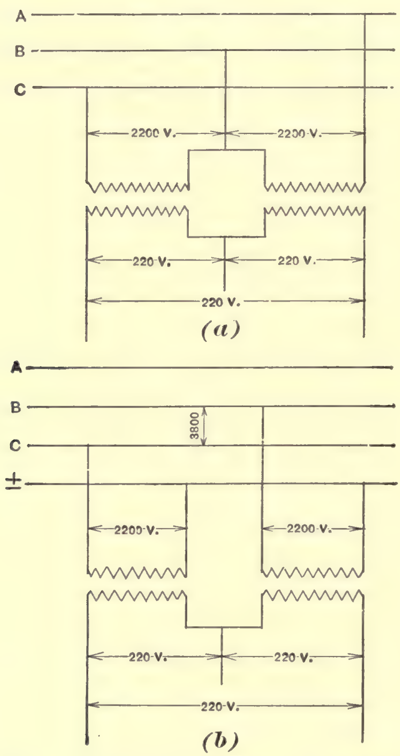


Fig. 79. Open Delta Secondary Connections.

purpose, one known as the open delta and the other as the T connection.

The open delta connection for a three-wire system is shown in Fig. 79 (*a*). This is merely an ordinary delta connection with one transformer left out. A simple rule by which this

connection may be kept in mind is that both primary and secondary are connected in series as if it were a three-wire Edison system. The middle wire of the line goes to the middle point between the transformer on both primary and secondary.

In order to reverse the rotation the two outside wires must be interchanged on the primary or two of the three crossed on the secondary side.

Fig. 79 (*b*) shows the open delta connection supplied from a four-wire three-phase system. In this case the primary is connected to two of the phase wires and the neutral wire. To reverse rotation on the primary side the phase wires should be interchanged.

With the open delta connection the current in the coils is 15.4 per cent more than it is with three transformers. That is, if three 5-kw. transformers are fully loaded by a given installation, they may be replaced by an open delta set of two $7\frac{1}{2}$-kw. transformers, but the coils of the $7\frac{1}{2}$-kw. units will be overloaded 15.4 per cent, at full load of 15 kv-a.

This is evident from an example. Assume that in a three-transformer installation, the current in the secondary line is 17.3 amperes. This places a load on the transformer secondary coils of $\frac{17.3}{1.73} = 10$ amperes. At 200 volts this is 2 kw. per transformer or 6 kw. in all.

If two 3-kw. transformers were used instead of three 2-kw. units, the capacity of the secondary coils would be 15 amperes. But with the open delta connection the current in the secondary coil is the same as the current in the line, and the 15-ampere winding must carry 17.3 amperes or 15.4 per cent overload.

With a three-wire three-phase system, power service may be given by the use of two transformers with the T connection on both primary and secondary, as shown in Fig. 80. The current overload is 15.4 per cent as with the open delta con-

nection. This scheme cannot be used with standard 2200-volt transformers on a four-wire system as the delta voltage is 3800. It is not possible to use this scheme with two transformers in series as the principle of operation requires that

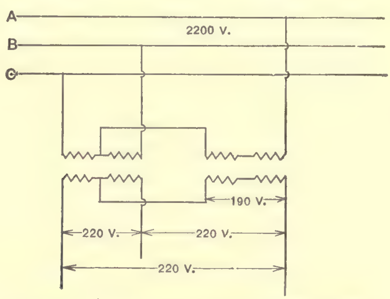


Fig. 80. T Connection, Three-phase.

the current passing to the transformer at the left, in Fig. 80, from the other transformer, divide and pass each way from the midpoint. Thus the magnetic field of one part balances the other. When two transformers are used across one phase the magnetic circuits are separate and the balancing reaction cannot take place. The terminal of the middle point of the primary is not brought out in standard distributing transformers and this plan is therefore not often used.

This connection has a slight advantage over the open delta in the three-wire system, as the pressure across the right-hand transformer is but 86.6 per cent of the line voltage, which reduces the iron loss in this transformer about 15 per cent. The inherent regulation is also somewhat better.

Two-phase Three-phase Transformation. — The T connection may be used in transforming from three-phase to two-phase or *vice versa*, as shown in Fig. 81.

It will be noted that one transformer must have a tap brought out so as to make the ratio of transformation on that

unit from 1906 to 220 instead of 2200 to 220 as in the other unit. Standard lighting transformers are not usually equipped with 86.6 per cent taps, but this connection may be quite closely approximated by the arrangement shown in Fig. 81 (*b*),

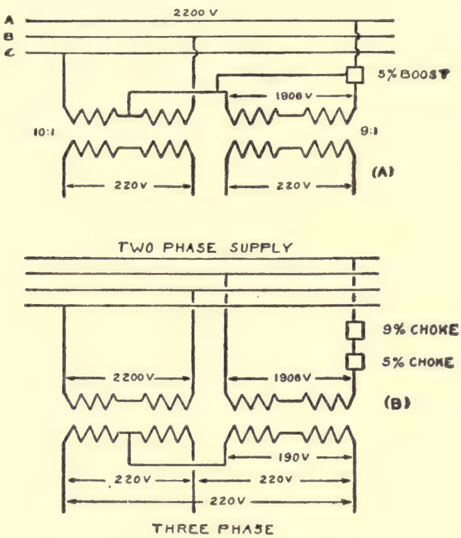


Fig. 81. Two-phase from Three-phase.

when the transformation is made from two-phase to three-phase. Standard 10 to 1 transformers are used, one phase of the two-phase supply being choked by two transformers, one of which is connected for 9.0 per cent choke and the other for 4.5 per cent.

If the pressure desired for the motor service were 230 volts and the primary pressure were 2080 instead of 2200, the left-hand transformer in Fig. 81 (*b*) should have a 9 to 1 ratio. With a 10 to 1 as the other unit, the 9 per cent choking transformer could be dispensed with.

In transforming from three-phase three-wire to two-phase with standard transformers, the pressure on the right-hand

transformer in Fig. 81 (*a*) must be raised by a booster. With a 10 to 1 transformer in the left-hand position, and a 9 to 1 at the right, the pressure must be raised 5 per cent by a booster. The primary coil of the booster must be connected from A phase to the center of the T connection, as shown in Fig. 81 (*a*), in order to get the pressure of the booster in phase with the current in the right-hand transformer. If only 10 to 1 transformers are available, the right-hand transformer is boosted 15 per cent instead of 5 per cent. If only 9 to 1 units are to be had, the left-hand transformer is choked 10 per cent and the right-hand unit boosted 5 per cent, to give 220-volt two-phase service.

In deriving two-phase 440-volt supply two sets of transformers may be used, putting them in parallel on the three-phase side and in series on the two-phase side.

It is impossible to derive 440-volt three-phase supply from a two-phase supply except with 440-volt transformers, since transformers will not operate in series on the T-connected side of such a combination.

Two-phase 220-volt service may be secured from a four-wire three-phase system with standard transformers by the use of three transformers connected as in Fig. 82. The unit at the left is a 10 to 1, connected from one phase to neutral. The others are 9 to 1, connected with their secondary coils in multiple, and are arranged as two limbs of a Y, so that a pressure of 127 volts is required at the transformer terminals to give 220 volts across the outer wires.

The three-phase system is unbalanced by this arrangement, since half the power is taken from one phase and the other half from the other two, making the balance in the proportions of 50, 25 and 25. The capacity of the transformers should be in these proportions.

It is possible to use 10 to 1 transformers for all, but if this is done it is necessary to install 15 per cent boosters in each

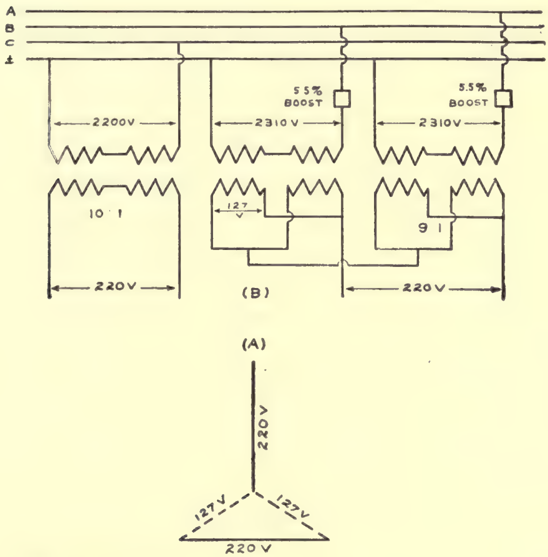


Fig. 82. Two-phase from Four-Wire Three-phase.

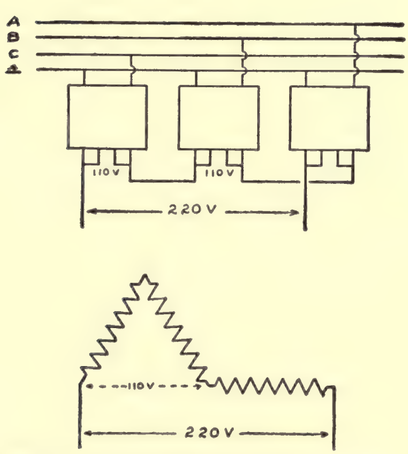


Fig. 83. Single-phase from Three-phase.

of the two phases supplying the right-hand transformers in Fig. 82. It is not possible to derive a four-wire three-phase system from a two-phase system with standard transformers.

Single-phase from Three-phase. — In connection with electric welding and work requiring single-phase energy in amounts so large that the unbalanced load is serious, the load may be distributed between the three phases by a scheme of connections shown in Fig. 83, in which equal currents are drawn from the three phases to supply 220-volt single-phase energy. Each transformer must have capacity to carry half the load, making the total capacity 1.5 times the load.

This plan is not applicable to a delta connected system as all the energy is supplied by one phase with that scheme of connection.

CHAPTER VIII.

PROTECTIVE APPARATUS.

Historical. — With the introduction of constant potential distribution some form of protection was necessary for generators and circuits which would save them from the effects of an abnormal flow of current when the circuit was accidentally crossed or short-circuited. This problem, which was fairly well solved for the conditions met in the early stages of the art, has reasserted itself with each increase in voltage and in power station capacities. Different solutions have been found for each case and the problem is still a live one.

In the early direct-current plants which were operated at about 110 volts the means selected for the protection of the apparatus consisted of fuses which automatically cut off the supply of electricity when more current was drawn from the circuit than it could safely carry. The presence of an overload or short circuit was thus indicated in a way which required prompt attention. It was found that lead, tin and similar soft metals having a low melting point had a relatively high electrical resistance. This combination of physical properties suggested an automatic cut-out in the form of a fusible connection inserted in the circuit. These early circuits were therefore protected by the insertion of short pieces of soft wire, known as fuses, which were so arranged that the melted pieces could readily be replaced after conditions on the circuit had been restored to normal.

Another and more elaborate method consisted of a solenoid connected in series with the circuit, and provided with a

plunger which tripped a spring and opened the switch in case of overload. This came to be known as a circuit breaker.

The use of fuses for protection against overloads and short circuits in low-tension lighting systems became universal because of their simplicity and low cost. The circuit breaker was used chiefly where the protective device operated frequently.

In its primitive form the fuse consisted of a piece of lead wire secured under binding screws at each end. The uncertainty of this form of contact resulted in fuses blowing when they should not, and tips of copper suitably slotted to fit the binding screws were added. The use of wood blocks was abandoned on account of risk of fire from the arc caused by the melting of the fuse. The use of slate and porcelain, while it eliminated the fire risk incident to the wood block, resulted in the chipping of the surface or the cracking of the block in case of the blowing of the fuse under short circuit with large amounts of power available. The use of porcelain for fuse blocks was prohibited except where the fuse was enclosed, and it was required that where slate or marble was used, a suitable barrier be placed between the terminals, the purpose of this barrier being to hold the heat of the arc away from the surface of the block.

Enclosed Fuses. — The danger of fire from the flash which occurs at the melting of the fuse when mounted on an open block led Edison, at an early date, to devise a form of enclosed fuse which could be easily renewed without the use of tools and which could be refilled when blown at small expense. This is the now familiarly known Edison plug fuse. Originally glass was used as the insulating medium and the cover was made removable, but it is now made of porcelain and the cover is attached so that it cannot be removed without the use of tools. This was found necessary to prevent the covers being left off. This form of fuse is one of the best and least

expensive methods of protecting low-voltage branch circuits carrying loads of 1500 watts and under.

The protection of lines carrying loads larger than 1500 watts is not satisfactory with the plug type of fuse as the explosive force is too great when short circuits occur. The copper-tipped fuse wire known as the link fuse serves this purpose economically, and is quite satisfactory for loads up to 50 kilowatts or more at low potentials. The open link fuse, however, is unsafe unless enclosed in a fireproof box, as the flash caused by the opening of the circuit constitutes a fire risk.

The danger arising from the use of open link fuses has led to the development of a large variety of enclosed cartridge fuses. Most of these consist of a tube of fibrous material in which the fuse is mounted, and a filling around the tube of certain fire-resisting powders which absorb the vaporized metal when the fuse blows and smother the arc. Connection is made at the ends by means of brass or copper terminals, copper being used on the fuses designed for currents of 60 amperes and upwards.

The use of nonporous substances in place of the fibrous tube has not been successful, as the pressure generated by the vaporization of the fuse metal within the tube must have means of escape. The concealment of the fuse wire within the tube makes desirable some device for indicating when the fuse has melted. This takes various forms, most of which employ a hole in the tube which permits a small portion of the arc to burn a paper covering, thus indicating at the surface that the fuse has melted.

The cost of installation and maintenance of cartridge fuses is necessarily several times greater than that of the link fuses. This has greatly retarded their adoption for low potential circuits, where the Edison plug and copper-tipped link fuses are most common. On 250 to 600 volt power circuits the use of cartridge fuses is quite general.

It is too frequently the case that where the designing engineer has provided a safe equipment of fuses of the cartridge type, the operating man permits its safety and effectiveness to be destroyed by the use of temporary devices designed to keep the circuit going but to postpone the expense of renewing the fuse. This condition has been improved somewhat by the introduction of cartridge fuses which can be refused at small expense.

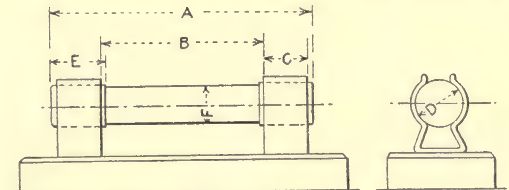
The sizes of cartridge fuses have been standardized by the National Electric Code in order to prevent the use of sizes of fuses which are greatly in excess of the rating of the circuit which they are designed to protect. Thus a fuse which is intended to operate at any current value from 0 to 30 amperes cannot be replaced by an enclosed fuse having a rating of over 30 amperes as the length and diameter of the tube are greater and the fuse larger than 30 amperes does not fit the clips on the 30 ampere block.

The sizes standardized by the National Electric Code are as in the table on page 177.

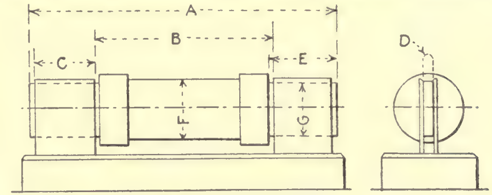
Operation of Fuses. — The operation of the fuse being dependent on the elevation of its temperature, the reliability of its performance on overloads depends upon the rate at which its heat is radiated. This is not so much of a factor in case of short circuit, as the temperature rise is so rapid that radiation has no appreciable effect.

Under normal load conditions the fuse may fail to carry its rated load because of insufficient opportunity for radiation or because of insufficient contact surface at its terminals, which may add to the heat instead of assisting in carrying it away. A fuse with a long length of wire between terminal clips will generally act at a lower current than one made of a short length, and a fuse mounted on lugs of liberal area will carry more than the same fuse connected to small lugs.

TABLE OF DIMENSIONS OF THE NATIONAL ELECTRICAL CODE STANDARD CARTRIDGE ENCLOSED FUSE



STYLE OF TERMINAL FOR CARTRIDGE FUSES 0-60 AMPERES



STYLE OF TERMINAL FOR CARTRIDGE FUSES 61-600 AMPERES

Form 1. Cartridge Fuse — Ferrule Contact. Form 2. Cartridge Fuse — Knife Blade Contact.

Voltage.	Rated capacity, amperes.		A Length over terminals, inches.	B Distance between contact clips, inches.	C Width of contact clips, inches.	D Diameter of ferrules or thickness of terminal blades, inches.	E Min. length of ferrules or of terminal blades outside of tube, inches.	F Diameter of tube, inches.	G Width of terminal blades, inches.		Rated capacity, amperes.
Not over 250	0–30	Form 1	2	1	$\frac{1}{2}$	$\frac{9}{16}$	$\frac{1}{2}$	$\frac{1}{2}$		Form 1	0–30
	31–60		3	$1\frac{3}{4}$	$\frac{5}{8}$	$\frac{13}{16}$	$\frac{5}{8}$	$\frac{3}{4}$			31–60
	61–100	Form 2	$5\frac{7}{8}$	4	$\frac{7}{8}$	$\frac{1}{8}$	1	1	$\frac{3}{4}$	Form 2	61–100
	101–200		$7\frac{1}{8}$	$4\frac{1}{2}$	$1\frac{1}{4}$	$\frac{13}{16}$	$1\frac{3}{8}$	$1\frac{1}{2}$	$1\frac{1}{8}$		101–200
	201–400		$8\frac{5}{8}$	5	$1\frac{3}{4}$	$\frac{1}{4}$	$1\frac{7}{8}$	2	$1\frac{5}{8}$		201–400
	401–600		$10\frac{3}{8}$	6	$2\frac{1}{8}$	$\frac{1}{4}$	$2\frac{1}{4}$	$2\frac{1}{2}$	2		401–600
Not over 600	0–30	Form 1	5	4	$\frac{1}{2}$	$\frac{13}{16}$	$\frac{1}{2}$	$\frac{3}{4}$		Form 1	0–30
	31–60		$5\frac{1}{2}$	$4\frac{1}{4}$	$\frac{5}{8}$	$1\frac{1}{16}$	$\frac{5}{8}$	1			31–60
	61–100	Form 2	$7\frac{7}{8}$	6	$\frac{7}{8}$	$\frac{1}{8}$	1	$1\frac{1}{4}$	$\frac{3}{4}$	Form 2	61–100
	101–200		$9\frac{5}{8}$	7	$1\frac{1}{4}$	$\frac{3}{16}$	$1\frac{3}{8}$	$1\frac{3}{4}$	$1\frac{1}{8}$		101–200
	201–400		$11\frac{5}{8}$	8	$1\frac{3}{4}$	$\frac{1}{4}$	$1\frac{7}{8}$	$2\frac{1}{2}$	$1\frac{5}{8}$		201–400

The action of enclosed fuses is in general somewhat more accurate than that of open link fuses on account of the more restricted radiation of the enclosed fuse.

The time required to cause a 5-ampere fuse to operate at different loads is illustrated in the curve of Fig. 84. This curve is typical of the action of fuses of all sizes, the absolute values varying with different types and capacities.

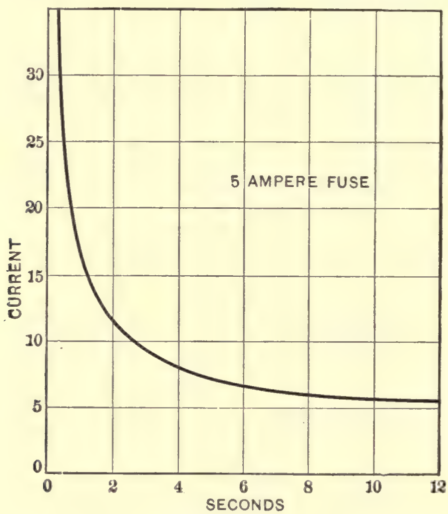


Fig. 84. Time Element of Fuse.

The law governing the operation of fuses was worked out by Preece in 1888. It may be stated with sufficient accuracy for general purposes in the form, Current $= a\sqrt{d^3}$, d being the diameter of the wire expressed in inches. The value of the constant a is different for each metal. For copper it is 10,244, for aluminum 7585, for lead 1379, for tin 1842 and for iron 3148.

For instance with a No. 10 B. & S. copper wire having a diameter of .102 inch, the fusing current is

$$C = 10{,}244 \times \sqrt{(.102)^3} = 334 \text{ amperes.}$$

The fusing currents for some of the smaller sizes of copper and aluminum wire are as follows:

Size Wire.	8	10	12	14	16	18	20	22	24	26
$\sqrt{(d)^3}$	.046	.0325	.229	.0162	.0114	.0081	.0057	.004	.0028	.002
Fusing current copper	472	334	235	166	117	83	58	41	29	20
Fusing current aluminum	349	246	174	123	86	61	43	30	21	15

Use of Fuses. — On low potential circuits the use of fuses inside of buildings is prescribed in detail by the National Electrical Code. The rules of the Code are based upon the general principle that each sub-division of load down to 660 watts must be protected by a fuse of such size as to operate at about the rated capacity of the circuit. Also that each group of circuits must be provided with a fuse at every point where there is a change to a smaller size of conductor. It is the purpose of the Code rules to have the fuse blow which is next in order from the source of supply. Thus, on the smaller circuits, the occurrence of a short circuit blows a small fuse and keeps the resulting arc down to the minimum size. The fire risk is thus kept at a minimum.

With outside distribution circuits, it is not necessary to provide so complete a system of fusing as that prescribed by the Code for inside work, since the fire risk is much less. Furthermore, the deterioration of fuses when placed out of doors, is apt to be such that they blow when no emergency exists, and service is unnecessarily interrupted.

Hence it is usually desirable to use as few fuses as possible with outside distributing lines. The number should not be reduced too greatly however, since the amount of service interrupted becomes excessive.

Alternating Current Primary Mains. — The standard system of distributing 2200 volt alternating current energy, by branches which are not inter-connected with other sources of supply makes the problem of placing fuses on such systems a difficult one. The practice is not fully standardized because of differences in local conditions and in the size of the system.

In smaller systems where the emergency man is close at hand and the conditions most likely to cause trouble are better known, it is usual to find more fuses used, than in a system embodying a larger number of circuits, and greater distances. In the larger systems where plenty of power is available to sustain a short circuit for a few seconds without danger to sub-station apparatus, it is usually considered preferable to depend largely upon the feeder circuit breaker at the substation.

Many cases of short circuit on overhead lines are temporary and clear themselves as soon as the circuit breaker opens. When this class of trouble occurs, the load of the feeder is interrupted for only a minute or two, whereas, if fuses are used, the load of the branch controlled by the fuse is interrupted for perhaps an hour or more until the emergency man can learn of the trouble and replace the fuse.

During severe lightning storms, fuses are especially likely to be blown by the discharge of arresters or by momentary discharge at other points. The replacement of fuses following a storm requires considerable time in a large system, and it is usually considered preferable to omit practically all primary main fuses, depending upon the station circuit breakers.

Fuses are sometimes used in cases where trees or other conditions are a frequent cause of interruptions on the smaller branches.

With the discontinuance of the use of fuses, it is necessary to provide a suitable disconnecting device, which can be used as a means of isolating sections of the circuit in emergencies

so that service may be restored on the remainder of the feeder. By this means the branch on which there is trouble may be located quickly if the principal mains are arranged so that they may be opened separately.

In the case illustrated in Fig. 85 the mains are radiated from a center of distribution at which the feeder may be quickly cut up into four parts, each of which may be discon-

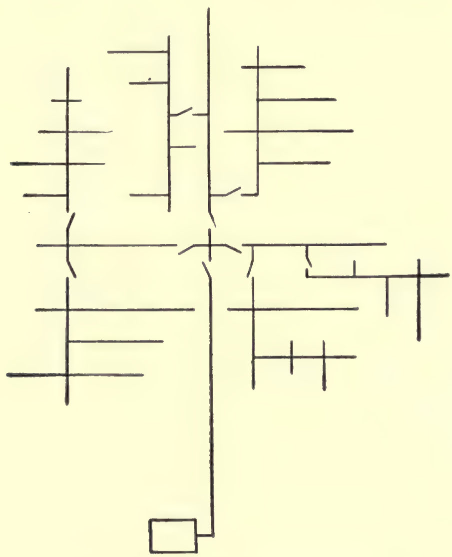


Fig. 85. Use of Disconnectives.

nected successively until the one which is short-circuited is located. Having determined which branch is in trouble, the emergency man may proceed to follow the route taken until he reaches the next junction point. Here similar tests are made to find out which sub-main is responsible for the interruption and so on until the trouble is located. These disconnectives may be single conductor disconnecting pot-heads or knife switches on small branches. A transformer fuse-block equipped with No. 8 or No. 10 copper wire is sometimes used.

Low-Tension Networks. — In overhead low-tension networks, using weatherproof insulated wire, the danger of short circuit is very slight if the lines are properly maintained, and it is therefore usual to omit fuses except at important points of supply so arranged that the occurrence of trouble will cut out reasonably small districts. Fuses at each junction are unnecessary, and involve more risk of trouble by blowing when they should not than of value in protecting the line against interruption. The work of repair is relatively quick, and it is therefore justifiable to risk larger areas than with low-tension underground lines.

In direct-current underground low-tension networks sectionalizing must be done with great thoroughness, owing to the density of the load, the length of time required to make repairs and the importance of the service.

Trouble on a distributing main or service taken from it must be limited to the block in which it occurs, and if lines are carried on both sides of the street it must be restricted to one side of the street. Trouble on an underground main is usually of such a nature that considerable time is required to make repairs. For this reason it is usual to place fuses at all junction points, so that in case of trouble the section affected will cut itself out at each end.

In the early Edison systems junction boxes were equipped with copper-tipped fuses made of sheet metal of lead and tin, which produced a large amount of vapor when they blew under short circuit and were subject to a tendency to depreciation, which caused them to heat and blow unnecessarily at times. This difficulty was obviated later by the introduction of sheet-copper fuses, such as those shown in Fig. 86 which are now in general use. This greatly reduced the weight of metal required and therefore the severity of the arc at the time of the blowing of a fuse. The section of the copper at the point where fusion takes place is designed to

carry its normal rated load without undue temperature rise and to fuse at about twice its normal rating. Two types of junction boxes which are used in connection with modern cable systems are shown in Figs. 86 and 88. The one shown

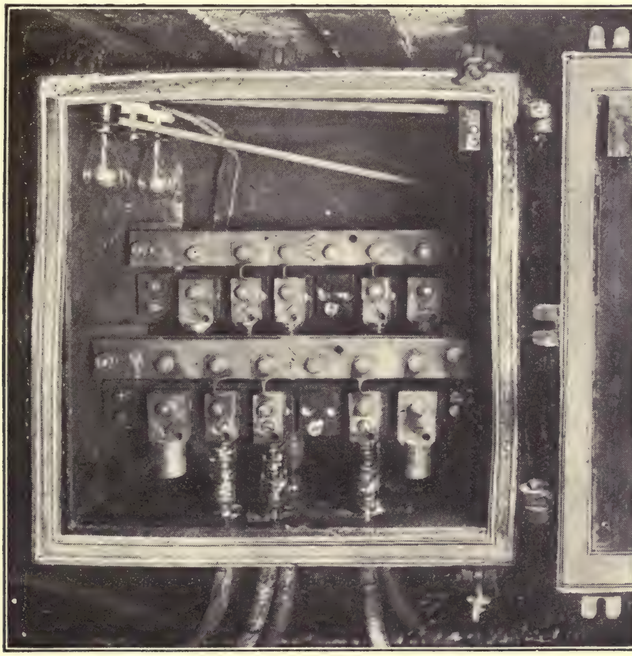


Fig. 86. Cable Junction Box, Manhole Type.

in Fig. 86 is installed on the wall of the manhole, while the other appears on the surface of the street.

The feeders in a low-tension network are fused at the point where they connect into the main system, to protect the network against trouble on the feeder. It is not usual in large systems to provide fuses on these feeders at the station since the operator on duty can open the switch and disconnect the feeder in case it is necessary. The likelihood of feeder fuses going out under emergency conditions when they should

not, makes it preferable to omit protective devices at the switchboard, and depend on the operator to disconnect in case of trouble on a feeder. Such trouble is very rare in cable systems and increased reliability is secured by this practice.

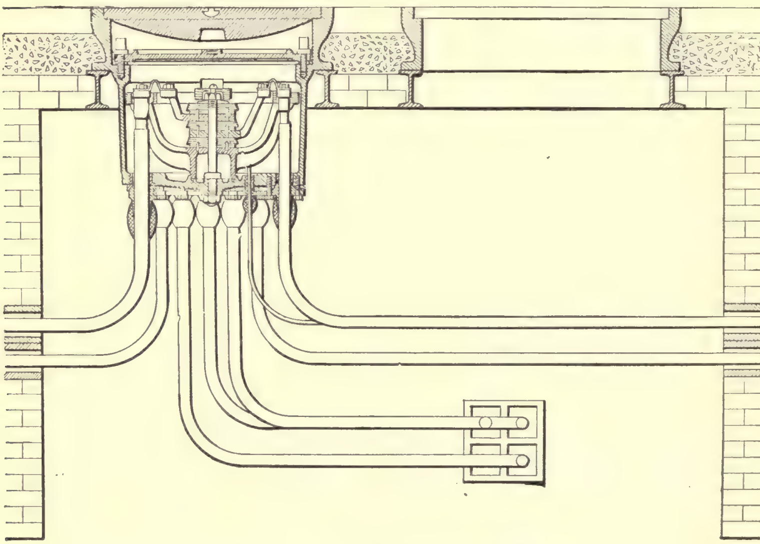


Fig. 87. Surface Type Junction Box.

Alternating-current Networks. — The establishment of Edison direct current networks with storage battery reserve in the central portions of the principal cities has left a comparatively small field to be occupied by alternating current low tension networks.

In the cities having direct current in the central portion, there are certain smaller districts served by alternating current in which the load density is such that the mains form a network. These districts, however, are usually so restricted that the network is not sufficiently large to warrant a low tension substation and feeders such as are employed in the

direct current district. The usual result in such cities is that there are small groups of transformers having interconnected secondary mains in the vicinity of an important street intersection, the district being served, however, by primary feeders as a part of the general alternating current systems. In other cases there is a main business thoroughfare flanked by residence sections on either side, so that secondary mains are continuous but are not intersected by other mains of importance.

With this class of secondary distribution there is little opportunity to utilize low tension junction boxes to advantage. It is therefore usual to connect adjoining secondary mains from different transformers together through fuse boxes, without fuses at the transformer except on the primary side. By this method a section of the secondary main is cut out in case the transformer supplying it should fail, while the advantages of parallel operation are secured under normal conditions.

In certain cities where there has been no direct current network established, there are areas in the central business districts in which loads of 1500 kw. to 5000 kw. are distributed where the geographical situation is such as to create a network of interconnecting mains, extending from 4 to 10 blocks in each direction. In such situations, the distribution is usually carried out by the use of primary feeders, serving transformers located in street manholes or in the basements of the larger consumers. In a few instances, the distribution is effected by means of low tension feeders serving a network of mains similar to a direct current network.

From the standpoint of protective apparatus, the use of low tension feeders and mains throughout is decidedly the preferable method as it obviates the use of high tension fuses or oil switches in manholes, and the introduction of high voltages into the consumer's premises.

With primary feeders, the transformer should be provided with primary fuses or oil circuit breakers, and the secondary mains must be fused at the transformer in order that the transformer may cut itself out in case it becomes defective. A special device known as a network protector has been used in some cities as a means of insuring the network against a general blowing of fuses due to the failure of a transformer. The device consists of a small auxiliary transformer which has its windings connected in series with the primary and secondary coils of the main transformer,

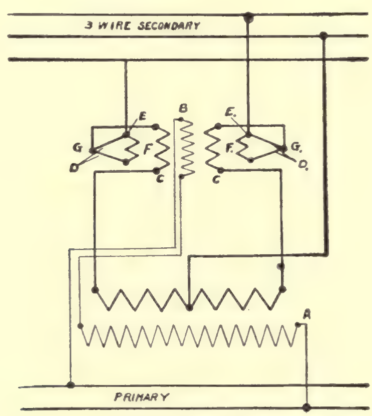


Fig. 88. Secondary Network Protector.

as shown in the diagram, Fig. 88. The core of the protector is magnetized by the current passing through the transformer, but the magnetic forces of the coils are normally in opposition to each other and so balanced that no voltage is generated in the secondary coil of the protector. When a primary fuse melts, the condition is no longer balanced and the secondary coil of the protector sends a large circulating current through the V-shaped fuse on the secondary side which immediately melts this fuse, thus disconnecting the transformer from the system on the secondary side. The capacity of the

secondary fuse is much greater than that of the transformer and is not likely to melt under any load which it is safe for the transformer to carry. The current circulated by the secondary coil of the protector is so large that the fuse is blown immediately and before the energy drawn from the secondary network has time to blow junction box fuses in the immediate locality.

The protector is very satisfactory as a preventative of general shut-downs caused by transformers burning out. It, however, may not prevent a general shut-down if the transformer which burns out is so large a proportion of the capacity in the immediate vicinity that the load shifted to other transformers blows their fuses and cuts them off. If two adjacent transformers are out simultaneously, there is quite likely to be a general operation of fuses which will shortly cut off the entire interconnected network. For this reason, large blocks of load such as hotels and theaters are usually served by separate transformers which are not connected into the network.

Where the load is so distributed that the transformers at each intersection are of approximately equal capacity, the disconnection of one transformer is not likely to be followed by anything more serious than a drop in pressure in that vicinity. With straightaway secondary lines and no mains intersecting at right angles, the probability of a spread of the trouble is greater as the capacity cut off is usually about 50 per cent of that of the two adjacent transformers and the overload may be sufficient to blow other fuses.

The primary main system is not usually extensive in districts where networks are found and no fuses are used for their protection. They should, however, be so connected by junction boxes or disconnecting potheads that any section of cable can be cut out in case of trouble or when work is to be done on it.

Transformer Fuses. — Line transformers should be provided with primary fuses of such size that they will not blow unnecessarily, and it is not advisable to attempt to protect transformers against ordinary overloads on this account. It is therefore usual to provide primary fuses having about twice the normal rated capacity of the transformer. The following table represents common practice on 2200-volt systems:

Kw. capacity.	Size fuse.	Kw. capacity.	Size fuse.
	Amperes.		Amperes.
1	10	15	15
2	10	20	15
3	10	25	25
4	10	30	25
5	10	40	50
$7\frac{1}{2}$	10	50	50
10	10	....	....

The porcelain type of fuse furnished with the transformer which has proven very satisfactory for transformers up to 20 kw. is illustrated in Fig. 89. The removable porcelain

Fig. 89. Transformer Fuse Block.

plug carries contacts on which the fuse is mounted, and the heat formed by the melting of the arc produces an explosive action which blows out the arc. This form of fuse is very satisfactory up to 15 or 20 amperes at 2200 volts.

For capacities above 25 amperes, there are various types

of fuses in use. The cartridge fuse is effective when kept dry, but when placed in a housing out of doors, it is difficult to prevent the filler from absorbing moisture and thus losing its arc smothering characteristics to a large degree.

The amount of energy dissipated in the arc when the fuse blows under short circuit is so great that it is a very difficult matter to design a fuse block which will not be seriously damaged, if not destroyed by the action of the arc.

Aluminum is used as the fuse metal very generally because of its low melting point and high conductivity, a combination which produces less vapor than lead wire. It is, however, subject to oxidation and crystallization which renders it somewhat troublesome in the capacities under 50 amperes.

Various forms of fuses other than the cartridge type have been devised from time to time for use on primary lines and larger sizes of transformers. Most of these depend upon the explosive action of the arc to blow itself out.

In one form an aluminum fuse link is placed between two blocks of lignum vitæ, one of which has a hole above the point where the fuse melts. The arc is blown out through the opening where the link fuses. The lignum vitæ is slow to ignite and tough enough to resist the pressure. This form of block is fairly satisfactory on loads up to 50 amperes at 2200 volts.

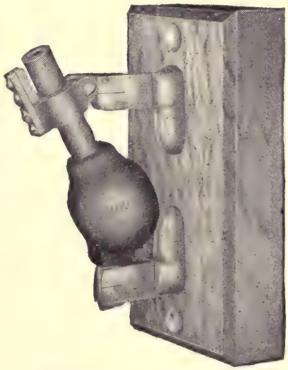


Fig. 90. Bomb Fuse.

Another on a similar plan consists of a fuse link carried between two blocks of asbestos board held firmly together by means of springs. When the fuse melts the metal is flattened out to a nonconducting condition and rapidly chilled by the close contact with the blocks.

Another form known as the bomb fuse, is placed in a reinforced fiber tube. When the fuse blows inside the tube the vapor is expelled at one end as in the firing of a gun. The fuse is readily renewed by detaching the tube from its carrier. (See Fig. 90.)

Other forms of fuse depend upon the action of a spring which separates the terminals widely when the fuse melts.

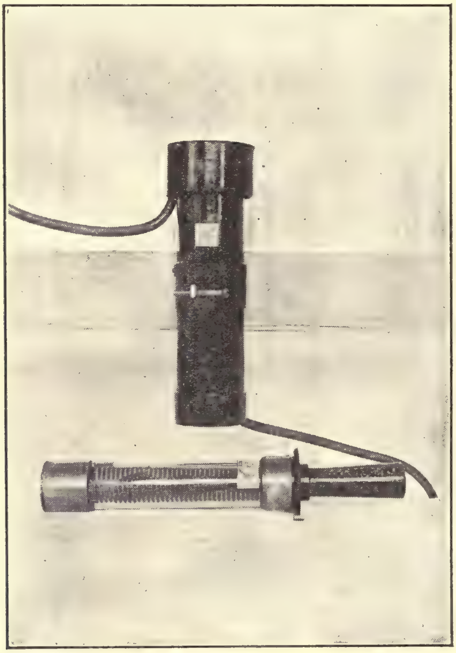


Fig. 91. Carbon Tetrachloride Fuse.

In one fuse of this type (Fig. 91) the fuse is enclosed in a glass tube which is filled with carbon tetrachloride which promptly quenches the arc.

Several types of fuse are available in which the fuse link is partially immersed in oil. When the fuse is vaporized

in the air above, the oil extinguishes the arc and protects the contacts from burning. This type is not always satisfactory in operation.

Circuit Breakers. — Under circumstances where automatic cut-outs operate at frequent intervals on circuits operating at high voltages or controlling loads of 100 kw. and upwards, the circuit breaker is the preferable means of protection.

In general the circuit breaker is expensive in first cost but inexpensive in operation, while the use of fuses involves a considerable maintenance charge but with a small first cost.

In mixed electric lighting and power systems the load is usually steady, and protective devices are not called upon to act except in case of line trouble. The use of fuses is therefore generally preferable in such systems except on feeder and transmission lines which carry large loads at high voltages where the use of fuses is not feasible.

On low-potential circuits the circuit breaker consists of a switch of suitable design, with which is combined a coil connected in series with the circuit so arranged that it will lift a movable core and release a spring-actuated mechanism which opens the switch. This plunger is designed to operate whenever the current exceeds a predetermined value.

Circuit breakers are commonly designed so that they may be adjusted to operate at any point between 80 and 150 per cent of their rated capacity. It has been found in practice a magnetizing force of about 1000 ampere turns is ample for the operation of the tripping device.

In high potential systems the design of the circuit breaker is modified somewhat by the fact that a series transformer may be installed at a convenient point in the main circuit and small wires carrying a few amperes may be led from the series transformer to operate the tripping coil of the circuit breaker.

On circuits operating at pressures above 600 volts the switch

is commonly of a design which breaks in oil. The use of the series transformer on such circuits serves the double purpose of providing a small current for operating the tripping device and of insulating the mechanism from the high-potential circuits.

Circuit-Breaker Control. — The operating mechanism of the circuit breaker is controlled by hand or electrically by solenoids.

In hand-operated breakers the energy required to open the

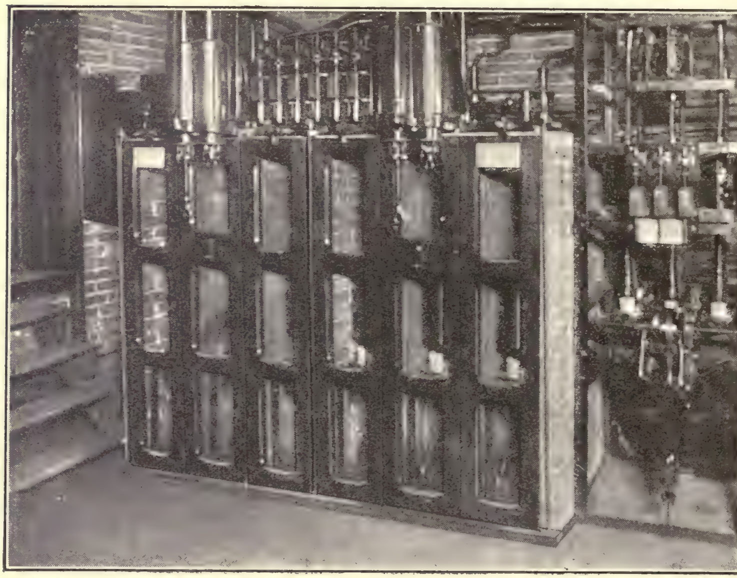


Fig. 92. Oil Circuit Breakers, Compartment Type.

circuit is usually stored in springs during the act of closing. The overload or reverse-current trip releases the spring mechanism which in turn opens the breaker.

In electrical operation the power for both closing and opening the circuit is supplied through solenoids or motors. The larger sizes and higher voltage breakers, such as those shown in Fig. 92, are usually controlled electrically on account

of the power required and because of the greater facility of operation permissible with remote controlled switches. The latter feature is quite essential in large systems where the number of switches to be handled during an emergency demands a system of control by which an operator may work rapidly and without great effort.

Since direct current is usually available in stations and substations from the exciter system, and is often safeguarded

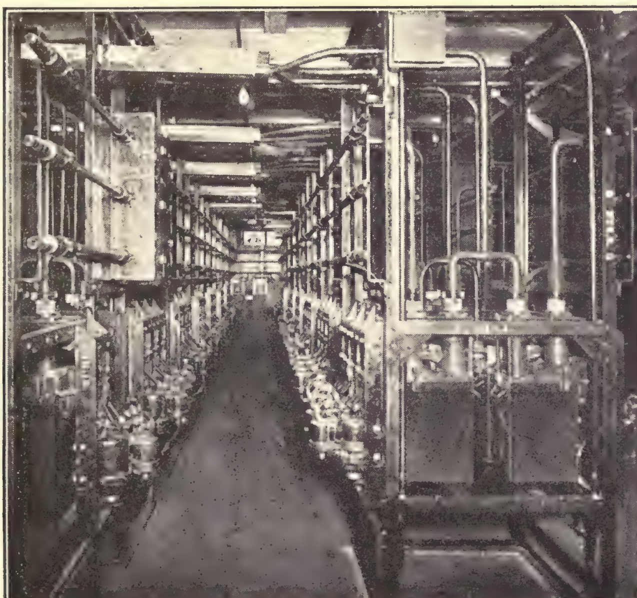


Fig. 93. Oil Circuit Breakers, Tank Type.

by a storage battery, it is usual to use direct current for the operation of solenoid controlled breakers, where possible.

Circuit breakers which are operated by motors may be controlled from an alternating current supply. Circuit breakers are designed to open all poles of the line simultaneously in three-phase three-wire systems. In two-phase systems and in the

four-wire three-phase system, single-pole or two-pole breakers are often used. A group of electrically controlled single-pole double-throw switches of the feeder type is shown in Fig. 93.

Relays. — With electrically controlled circuit breakers the protective device is really the relay which energizes the control circuit. This consists of an alternating-current solenoid energized by a current transformer and having a plunger which closes the direct-current circuit and thus energizes the mechanism of the circuit breaker as shown in Fig. 94.

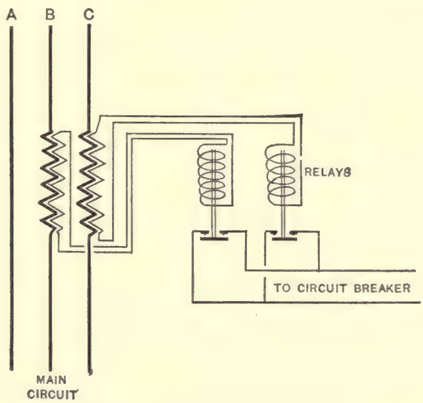


Fig. 94. Relay Connections.

In order to prevent the operation of the circuit breaker under momentary rushes of current, it is usual to design the relays for operation with an inverse time element. That is, with the relay set to operate at 100 amperes after 10 seconds, it will operate at about 300 amperes in five seconds and almost instantaneously at 1000 amperes. This characteristic gives prompt action in opening the circuit under short circuit, while reducing the liability of unnecessary interruption under short overloads.

This result is accomplished by damping devices such as

leather bellows. The leather bellows has proved the most satisfactory in view of its simplicity and reliability.

The arrangements of relays on a feeder or transmission line must be that the occurrence of a short circuit between any two wires will operate the breaker. On single-phase circuits one relay is sufficient to accomplish this. On two-phase three-wire systems carrying lighting and power it is desirable to provide separate relays and circuit breakers for the two outer wires so that only one phase is interrupted in case of trouble, which does not short-circuit both phases. This is also true of the four-wire two-phase system. In the three-phase three-wire system the occurrence of a short circuit between any two wires interrupts service on all phases, and relays are required in two wires so that at least one will open the circuit in case of trouble on either phase. The circuit breaker is therefore a three-pole breaker.

In the four-wire three-phase system or in a three-wire three-phase system having the neutral point of the generator winding grounded, it is essential that relays be installed in each phase wire since the occurrence of a ground on either phase conductor results in a short circuit. In the four-wire system only the relays on the phases affected come into action. In case of a ground on one phase the circuit breaker on that phase opens without interrupting lighting service on the other two phases.

Transmission System Protection. — Where there are several radial transmission lines terminating at the same point, or at points which are connected by tie lines, it is desirable to operate them in parallel. When this is done, it is necessary that suitable relays be provided at the terminal point on each line.

If this is not done, a fault in either line will continue to draw energy from the terminal bus, after the circuit breaker

on the faulty line at the generating station has opened. This is quite likely to cause the other lines to open and thus interrupt the entire supply to the substation.

It has been very difficult to develop reverse energy relays which would operate reliably and only in recent years have devices of this type been sufficiently dependable to warrant their use in large systems.

In some cases, operating engineers have found it possible to operate in parallel without reverse energy relays because of the fact that all transmission lines were underground and cable trouble was infrequent.

In systems operating lines on the radial plan, the inverse time element type of overload relay is used to protect the line where it is not normally in parallel with other lines. Where two or more substations are supplied in tandem, the definite time limit relay is used in order that when trouble occurs on a cable beyond the first substation, only that part of the line which is in trouble or beyond the section which is in trouble is cut off. This is accomplished by setting the relays on each successive section to trip a little sooner than the one next nearer to the point of supply. With the definite time relay, this can be done quite accurately. The use of the definite time relay increases the time required to cut off the short circuited cable when it happens to be in a section near the generating station and this is likely to make the damage greater than it is with inverse time limit relays under similar circumstances. This danger is, however, materially reduced where suitable reactances are employed to limit the severity of short circuits.

The operation of lines in a ring system with the ring normally closed has not been generally practiced in America because of the lack of suitable protective relays for this condition.

In Europe, however, progress has been made in this direc-

tion and there are several systems operating in parallel with protective systems which are giving satisfactory results, and with distinct additional commercial advantages.

The largest of these systems was developed by Merz and Price in the Newcastle district in England, where a very extensive system of both cable and aerial lines is in operation.

The Merz-Price system is based upon the principle that the relays become operative only when a defect occurs in a line which draws energy from both ends. While energy is passing through the cable in either direction, the forces are balanced and the relays do not act. Each section of line between substations or junction points must have its own protective relays, and only the section which is in trouble is cut off by the operation of the relays.

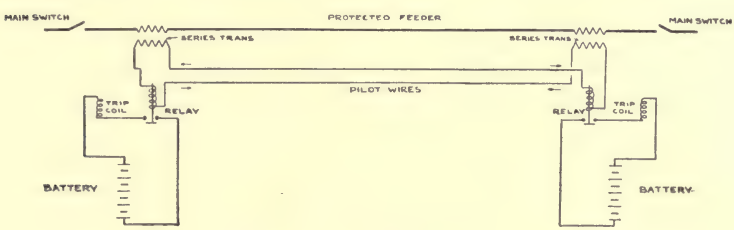


Fig. 95. Merz-Price Relay.

In Fig. 95 it will be seen that there is a series transformer in each conductor at each end. The secondaries of these current transformers are connected in opposition to each other through pilot wires. There is an ordinary relay at each end by which the switch controlling the section of line is actuated.

When a short circuit occurs within a section, energy flows in opposite directions from each end toward the fault and this reverses the potential in one of the current transformers causing a strong current flow through both relays and opening the switches. This current flow does not disturb the switches in adjoining sections and the trouble on the line

therefore causes no interruption of service in any of the substations.

The application of this system to a network of lines and a group of substations is shown in Fig. 96. This group includes a number of industrial substations having loads of 100

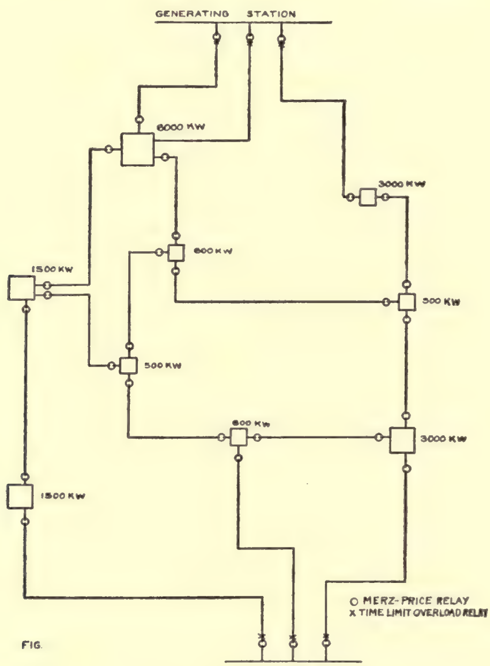


Fig. 96. Protected Transmission Network.

to 1000 kw. and others serving general distributing systems aggregating larger amounts. The advantage of parallel operation is usually greatest with smaller substations as the larger substations have loads which more nearly fit the capacity of the lines supplying them.

The connections from the ring or network to substations are made through ordinary overload relays where there is

only one set of receiving apparatus. Where there are transformers or other apparatus in parallel, they are protected by a local Merz-Price outfit so arranged that if a transformer or synchronous machine is short circuited it is immediately cut out on both sides.

In this class of protective equipment where the current transformers are near each other, the secondaries are put in series and the relay is of the closed circuit type, operating only when the current is reduced in value materially. This is known as "current balancing," while the plan used with lines is called "e.m.f. balancing." The use of current balancing is of course undesirable on lines on account of the loss in the pilot wires at great distances.

For certain classes of installations, the balancing may be done magnetically, by opposing the magnetic fluxes due to the current from the series transformers to each other in a common core. The relay is actuated in this case by an unbalanced magnetic field resulting from energy flow into the apparatus from both ends.

The chief objection to the Merz-Price system is the necessity for pilot wires, as these add approximately 10 per cent to the cost of the line and therefore are usually carried in a cable whether the line is underground or overhead. If overhead, they are supported by a steel cable to insure against breakage during high winds as fully as possible.

The current transformers for e.m.f. balancing must be specially designed for operation on open circuit and have capacity to deliver the energy needed to actuate the relays over the long pilot wire circuit. They must also be carefully adjusted so that each pair has the same ratio of transformation under all conditions of operation.

There have been various modifications of the Merz-Price system suggested and a few have been installed on a moderate scale.

Hochstadter has avoided the use of separate pilot wires in the system in Cologne, where the cable is made with copper ribbon worked into the insulation in such a way as to be well separated from the conductors carrying the main power supply. These ribbons serve as the pilot wires, thus avoiding the necessity for a separate duct system or separate lead sheath.

A still further simplification has been effected in a scheme using split conductor cable, as shown in Fig. 97. Each polarity of a three-phase cable is divided into two equal parts which are insulated from each other, making it virtually a

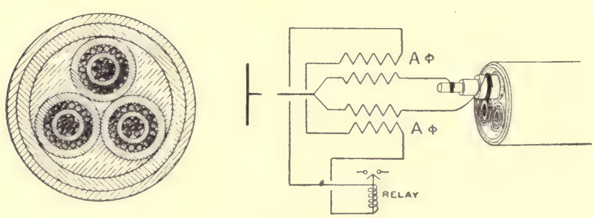


Fig. 97.

six-conductor cable. The current divides equally between the two parts of a conductor under normal conditions. In case of a fault in the cable, it is quite probable that one part of the conductor will draw more current than the other, as the parts are separately insulated. The balance between the two current transformers at the terminal points which are opposed to each other is destroyed and the relays operate to open the circuit breakers at each end, cutting out the faulty cable. The principal objection to this plan is the complication introduced in cable jointing operations by the splitting of conductors. This system has been used in recent years in England in preference to the pilot wire scheme.

A method of protection, based upon the principle of cutting out the faulty section of cable, which does not involve

pilot wires, is shown in Fig. 98. The various sections of a ring are provided with relays which are uni-directional, that is, will operate only on energy passing in one direction through them. By placing such relays in each section of the line and connecting them to operate in opposite directions a fault in the cable of any section will cause the two relays for that section to operate the circuit breakers and cut the section out. However, in this scheme, the energy passing to the fault must pass through adjoining sections as well, and may cause one end of those sections to open unless the relays are provided with

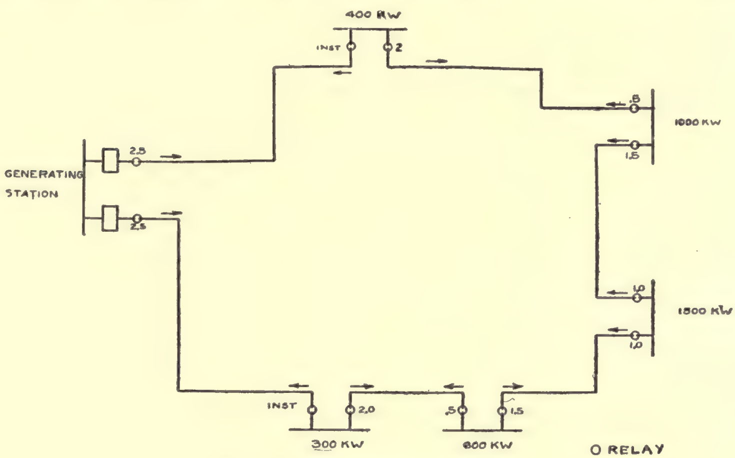


Fig. 98. Reverse Energy Relay.

definite time limit adjustments, which are so set that the sections farthest from the source of supply will operate first. This means that the time setting of relays must be highest at the station end and be gradually reduced as each successive relay is passed, until, at the far end of the ring, the setting is practically instantaneous. These settings are indicated in seconds in Fig. 98 for each relay. It is apparent that this scheme is not adaptable to an extensive network but applies to ring systems having not over 5 or 6 substations or wholesale

consumers. If the number of stations supplied is larger than this, the time setting of relays at the supply point may be so great that in case of a fault in the section of cable nearest the point of supply, the time required to open the breaker may be sufficient to cause serious injury to the supply station apparatus.

Protection from Lightning. — Overhead lines are subject to the influence of static electricity in the atmosphere, and in parts of the country where lightning storms are common during the summer months, the problem of protection of service and equipment is often a difficult one.

Electrostatic charges accumulate on the open conductors of a circuit, at times when charged clouds are passing above the line, or by the gradual transfer from drops of rain, fog or snow as they touch the wires.

The sudden release of a charge which accompanies a lightning stroke from cloud to cloud or to earth, liberates the induced charge on the line and causes an abrupt rise of potential which must find a path to earth. It is this sudden release which is most likely to puncture insulation and injure apparatus. This discharge is in the nature of an impulse which is very severe in the immediate vicinity of the lightning flash and rapidly diminishes in force as the wave travels along the line. In lines carried on wooden poles, the discharge may go to ground over the insulators and splinter one or two poles without being felt seriously by equipment only a few hundred feet distant.

The function of a lightning arrester is to provide a point at which the static charge or the impulse induced by a lightning stroke may pass to earth without injury to line insulators, transformers and other equipment.

The arrester must further be so designed that though it will permit the high potential charge to be relieved, it will

not permit the working potential of the line to maintain an arc when it is established.

This result is accomplished with reasonably good success in several types of lightning arresters which are described in a following paragraph.

In primary or transmission systems not having a grounded neutral point, the problem of stopping the flow of power after the lightning discharge has passed is somewhat easier of solution than with a grounded neutral, as the power current must pass through two arresters in series. With a grounded neutral, every discharge to ground is followed up by line potential which requires a higher resistance and more gaps in series to hold the power current in check. However, the arrester on the neutral conductor in such systems may be a 300-volt arrester of simple design.

Types of Arresters. — The natural method of establishing a path which will have a high resistance to the flow of the line current is to arrange a suitable number of air gaps. The early 1100-volt single-phase systems were protected by arresters of this type very satisfactorily. These arresters failed, however, when used at 2200 volts with ample power at the source and it was necessary to add a graphite resistance rod in series with the gaps. It was also found necessary with grounded neutral systems to abandon the use of iron cases, substituting wood therefor. This practice was found safer for all systems and wood boxes are now standard for potentials of 2000 volts and upward.

At potentials below 1000 volts a simple air gap is found sufficient in most cases. An arrester of the 300-volt class shown in Fig. 99 is used for the protection of extensive overhead secondary systems and for the neutral conductor of primary systems having a grounded neutral.

For 2300-volt distribution there are three types in very

general use and a number of others which have been used to some extent. The spark gap arrester with resistance, the circuit breaker type and the compression type are the ones in most general use. They were developed and introduced in the order named.

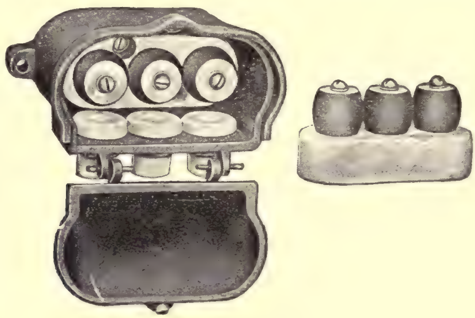


Fig. 99.

The spark gap arrester has, in recent years, taken the form of a multi-path or low equivalent arrester. Fig. 100. The spark cylinders are of non-arcing metal to prevent the arc being maintained by the line voltage.

In this arrester the proportions of the parts are so designed that the high frequency lightning discharges pass across the sparking cylinder gaps to earth, while potential surges at lower frequencies follow the paths through the resistance rods. It thus takes care of high potential disturbances of all kinds whether they originate from atmospheric electricity or from surges of energy within the system.

This type of arrester, Fig. 100, is also used for transmission lines up to about 10,000 volts. Its wide range is more valuable in this field than in 2300-volt distribution.

A modified form of the gap and resistance arrester, which includes a circuit breaker, is illustrated in Fig. 101. This arrester has the resistance between the gaps, one set of gaps being on the line side and another set on the ground side.

The gaps on the ground side are shunted by a solenoid having a plunger which is lifted by the current passing through the coil and thus acts as a circuit breaker for the current in the solenoid.

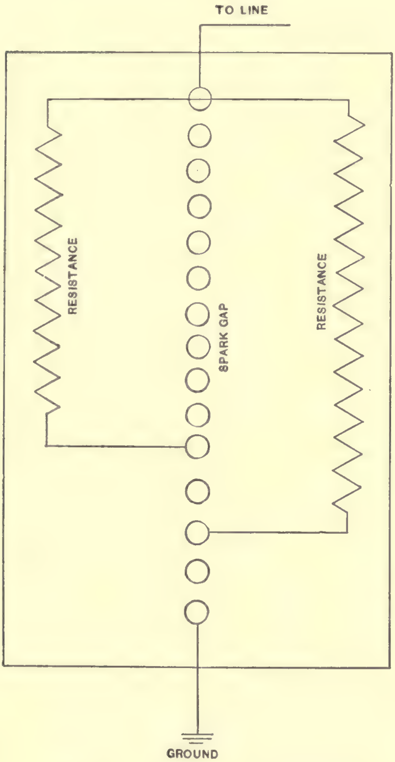


Fig. 100. Multi-path Lightning Arrester.

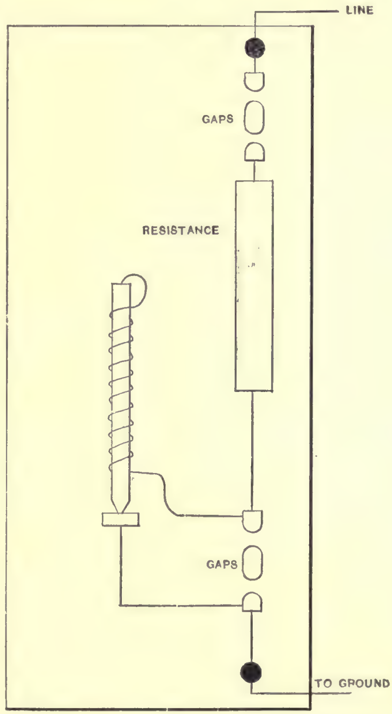


Fig. 101. Solenoid Type Lightning Arrester.

The lightning discharge passes across the gaps to ground as the inductance of the solenoid is too high to permit it to pass through it. If the line current holds across the gaps on the line side of the resistance, it passes through the solenoid, thus operating the circuit breaker and extinguishing the arc.

A specialized form of the spark gap arrester is shown in Fig. 102. This is known as the compression chamber arrester and consists of a series of spark gaps arranged inside a porcelain tube, in series with a resistance rod which occupies the upper part of the tube. The gaps are made more susceptible to discharge by grounded pieces of iron in "U" shape, called antennæ, which are placed across the bottom of the tube and extend several inches up the sides. These serve to modify the potential gradient of the gaps so that about twice as many gaps can be used in series with the resistance as it is possible to use without the antennæ. This enables the 2300-volt arrester of this type to extinguish the arc with a resistance of about 25 ohms.

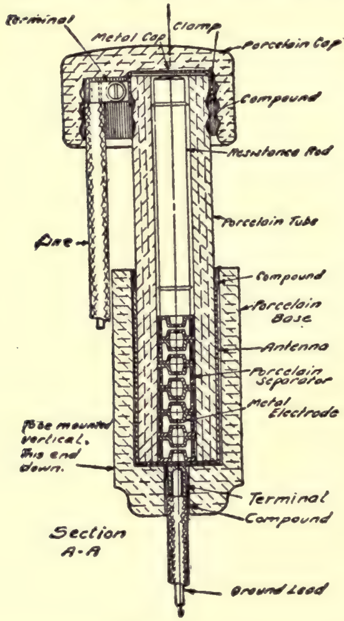


Fig. 102.

The top of the tube is sealed so that the heat of a discharge produces a pressure inside the porcelain, and this in turn assists in putting out the arc.

The line terminal is brought out at the top and the ground terminal at the lower end of the tube. The antennæ are covered by a bracket of porcelain which serves as a means of support on the cross arm. No enclosing box is required.

The electrolytic type of aluminum cell arrester (Fig. 103) is quite generally employed at voltages of 15,000 and upward.

This arrester is based upon the fact that aluminum when placed in a suitable electrolyte is quickly coated with an insulating film of oxide when current is passed through it. This

almost entirely stops the flow of electricity until the pressure is raised above the critical value of about 350 volts per cell.

A discharge of lightning may thus pass through an arrester made up of a number of cells in series, but as soon as it has passed the line, current cannot follow since the film at once shuts off the flow of current. The great severity of a stroke near the arrester sometimes forces sufficient energy through the cell to melt a hole in the aluminum cones necessitating their replacement.

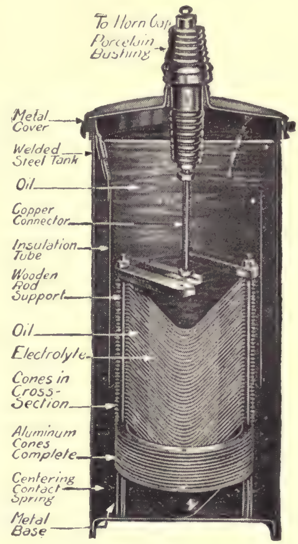


Fig. 103.

This kind of injury is not peculiar to the aluminum cell, however, as all types of arrester are at times damaged by discharges which pass large quantities of electricity.

The film of oxide upon which the action of the arrester is based is gradually reduced by the electrolyte unless there is a flow of current passing through the arrester. Under continuous application of voltage, there is a small leakage current which is attended by an appreciable loss of energy and resultant elevation of temperature.

It is therefore usual to connect the arrester to the line through a horn gap of such design that there is normally a small air gap between the line side and the arrester connection. One side of the horn is hinged and connected to levers so that an operator may easily throw the two horns into contact and thus allow a charge to pass into the arrester. This charging operation is usually performed daily and is attended by a momentary rush of current except where current limiting resistances are provided to prevent it. (Fig. 104.)

The aluminum cell arrester is therefore best adapted to situations where there is sufficient expert supervision to insure its proper maintenance and operation as at power-stations and substations. It is not employed on distribution lines

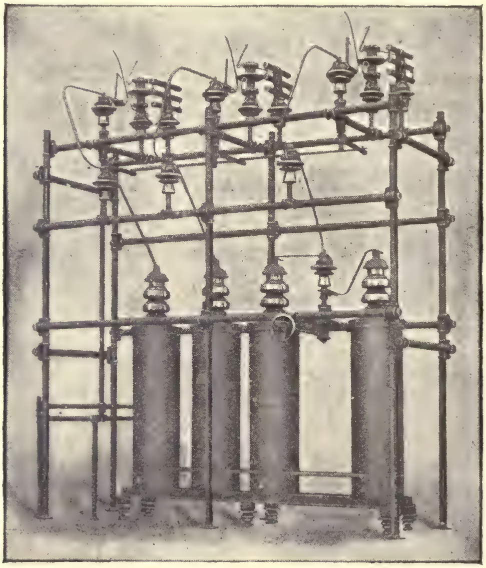


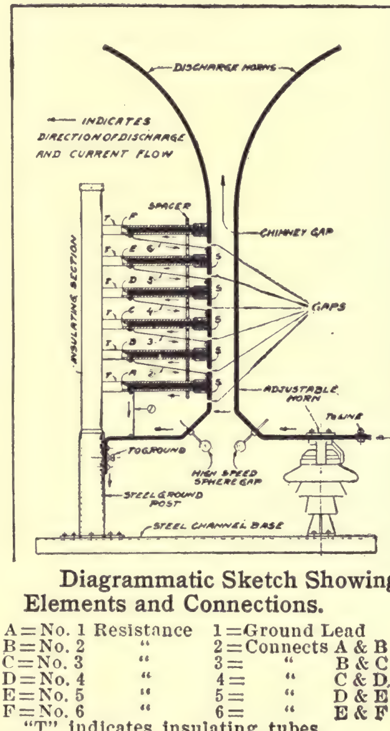
Fig. 104.

because of the necessity for close supervision and frequent charging.

The horn gap arrester is used to a limited extent for the protection of transformer installations supplied direct from a transmission line in rural districts or in villages served from such lines. The arc is extinguished by the flaring horns which gradually increase the length of the arc to the breaking point. The rush of current when no resistance is provided is usually sufficient to open the line circuit breaker, and this limits the usefulness of this type of discharge point. It is usually provided with resistances where its use is necessary. In a large

system, the presence of open arcs such as those produced at the horn gap is quite likely to cause pressure rises elsewhere in the system which may endanger apparatus and interfere with service. A special form of horn gap arrester with resistances attached is illustrated in Fig. 105.

Location of Arresters. — The problem of placing arresters on distribution circuits where they will be most effective, and the determination of the proper number to use in proportion to the apparatus protected is a difficult one. The fact that a discharge will take the nearest path to ground rather than follow the line a few hundred feet to go across the gaps of a lightning arrester is now quite well established. The presence of an arrester within 300 feet of a transformer or cable pole is often of no value in saving the insulation from puncture and destruction. The arrester must be on the same pole with the transformer in order to assure protection of the unit in a severe lightning storm.



Diagrammatic Sketch Showing Elements and Connections.

A = No. 1 Resistance		1 = Ground Lead	
B = No. 2	"	2 = Connects	A & B
C = No. 3	"	3 = "	B & C
D = No. 4	"	4 = "	C & D
E = No. 5	"	5 = "	D & E
F = No. 6	"	6 = "	E & F

"T" indicates insulating tubes.
"S" " copper segments.

Fig. 105.

The effect of placing an arrester on the transformer pole as compared with arresters placed elsewhere has been studied throughout a period of years by the engineers of several large

central station systems, the most extensive study having been made in Chicago.

Several thousand transformers in certain districts were provided with arresters on the same pole. In other districts, the arresters were near the large transformers or distributed at intervals of about 1500 feet along the line, there being approximately 40 per cent as many arresters as transformers. Record was kept of all transformers which burned out during storms, during several seasons, with the result that in the district where the arresters were placed on each transformer pole, the losses of transformers were negligible, whereas in the other districts the losses amounted to an average of about 1 per cent per annum. The seasons of very severe lightning produced losses of about 2 per cent while other seasons ran as low as $\frac{1}{2}$ per cent.

An analysis of the figures, which are based on the records of performance of about 15,000 transformers, shows that the smaller units are somewhat more susceptible to injury. This is particularly true of the sizes below 5 kw.

The investment in lightning arresters required to reduce the average losses from 1 per cent per annum to practically nothing is too great to result in a net saving, and is not justified as a means of reducing the net loss.

However, in comparing the cost of an arrester equipment with the possible loss of a transformer of one of the larger sizes, it is found that a point is reached at about 20 kw. where the arrester equipment is justified for each transformer.

In connection with the Chicago experiment, a record of transformer fuses blown during storms was also kept, as it has been observed that there were many fuses blown during storms, but without apparent injury to the transformer. The analysis of these fuse records revealed the important fact that the presence of an arrester on the pole was an almost sure pro-

tection from unnecessary blowing of fuses and greatly increased the security of the service during storms.

This feature of the scheme of protection has therefore been extended by some of the large companies as a matter of giving good service until it is standard practice with them to install a lightning arrester with every transformer of 5 kw. or larger capacity.

On transmission circuits, the use of arresters is usually limited to substations, cable terminal poles, and transformer installations where such are made at points along the line. It is not desirable to attempt to protect the line itself from lightning in most cases. Insulators have been safeguarded in some cases by the use of an arcing ring or ground rod, the purpose of which is to give the arc an opportunity to go to ground without damaging the insulator. This device is used where trouble with punctured insulation has been excessive and where the failure of an insulator made it desirable to put the line out of service. The short interruptions due to the operation of the arcing gaps are found less objectionable than the more extended interruptions due to damaged insulators.

In districts where several towns are supplied by out-of-door transformer installations, the use of arresters is necessary at each installation.

CHAPTER IX.

OVERHEAD CONSTRUCTION.

The use of overhead construction is an economic and practical necessity in a large part of the territory supplied in every city. The investment per kilowatt of maximum load for overhead lines is from 15 per cent to 30 per cent of that required for underground construction and it is obvious that overhead construction must be used for as much of the distributing system as is feasible in order to keep the investment within profitable limits.

Overhead construction is, therefore, very generally used in the outlying parts of the larger cities and in all parts of smaller cities. It is usually not feasible to use overhead construction in congested business districts, as there is not room for the equipment in many cases, and its unsightly appearance is very objectionable to the general public. In most of the large cities the franchise under which the business is conducted requires underground construction in the congested districts. In many cases the objection to overhead lines may be greatly minimized by locating them in alleys, thus keeping the unsightly equipment out of sight and avoiding the defacement of fronts of buildings by service wires.

The use of overhead lines began with the earliest lighting systems which were installed for street lighting.

Poles and cross arms had been used for the support of overhead lines for many years in connection with telegraph work, and it therefore only remained for the electric lighting engineers to make slight modifications in the spacing of the wires and in the type of insulator employed.

Poles. — The usual form of overhead construction in American practice consists of wooden poles with the wires carried on cross arms.

The woods which are best suited for pole work in America are the Northern white cedar, Western red cedar, chestnut and pine. Other woods are used, but to a limited extent.

White Cedar. — This grows with a natural taper of about 1 inch in diameter to every 5 or 6 feet of length, except near the butt of the pole, where it flares out somewhat larger, making a very substantial and rigid pole. The sapwood, which is about 1 inch thick, is soft enough to make the use of spurs very easy in climbing. The surface of the pole is comparatively free from knots and it is lighter than chestnut or pine.

This species of cedar grows in the region about the Great Lakes and when used in the north central part of the United States has a life of 15 to 25 years, without treatment.

The trees are cut in fall and winter and seasoned several months before shipping, as they lose materially in weight in the first few months by evaporation.

The standard National Electric Light Association specification for the dimensions of this type of poles appears in the following table.

Circumference of white cedar poles.

Length.	Class *A*.		Class *B*.		Class *C*.	
	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	24	37	22	32	18.75	30
30	24	40	22	36	18.75	33
35	24	43	22	39	18.75	36
40	24	49	22	43	18.75	40
45	24	50	22	47	18.75	43
50	24	53	22	50	18.75	46
55	24	56	22	53	18.75	49
60	24	59	22	56	18.75	53

The dimension 6 ft. from the butt is essential with the type of pole because of the fact that the butt often flares considerably, making a butt measurement an inaccurate gauge of the strength of the pole.

It is usual to reject poles having a bend in more than one plane, or any crook which will make it unsightly or difficult to line up with other poles. Poles should not have a sweep in one plane of more than about 12 inches.

Chestnut. — The growth of chestnut timber for poles is found in the New England States, and in the states including the Appalachian range as far south as North Carolina.

The forests are reproducing to a considerable extent due to the fact that the stump of the tree sprouts and grows more rapidly than the seedling. The growth of the tree requires about 40 years from the sprout and 50 years if grown from the seed.

It is considered most desirable to cut the trees in fall and winter as this produces more vigorous sprout growth. Further, as with other woods, seasoning takes place more gradually and with less tendency to produce checking in the pole.

The tree should be cut near the ground in order to include the flaring portion of the trunk in the butt of the pole.

The chestnut pole is considerably heavier than cedar poles of similar dimensions, and is more likely to have knots which affect its appearance unfavorably. The sapwood is thinner and harder than that of cedar and it is therefore somewhat less adaptable to the use of spurs in doing line work. Its somewhat greater density also seems to be responsible for a somewhat lower insulating value in damp weather.

The dimensions of standard chestnut poles should be as follows:

	Circumference in inches.					
Length of pole.	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	24	....	22	....	20	30
30	24	40	22	36	20	33
35	24	43	22	40	20	36
40	24	45	22	43	20	40
45	24	48	22	47	20	43
50	24	51	22	50	20	46
55	24	54	22	53	20	49
60	24	57	22	56	20	....
65	24	60	22	59	20	....

Western Cedar. — This is found chiefly in Idaho and Washington, and is used very generally for poles in the western part of the United States. The trees are cut preferably when the sap is down, and are trimmed and peeled immediately in order to facilitate seasoning. The poles are hauled and piled until ready for shipment except where streams are available as in the Puget Sound district. Here they are kept in fresh water until shipped. If kept in salt water for more than 30 days they are attacked by the teredo.

The Western cedar grows with less taper than the Michigan white cedar, it having about 1 inch decrease in diameter, for each 9 feet of length when measured from the butt end. Its weight is approximately the same. Western cedar grows straight and quite clear of knots and twists and presents a neater appearance than any other kind of wood pole.

The standard dimensions should be specified as follows:

	Circumference in inches.					
Length, feet.	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	28	34	25	31	22	28
30	28	37	25	34	22	30
35	28	40	25	36	22	32
40	28	43	25	38	22	34
45	28	45	25	40	22	36
50	28	47	25	42	22	38
55	28	49	25	44	22	40
60	28	52	25	46	22	42
65	28	54	25	48	22	43

Pine. — There are several varieties of pine which are available for pole work, but none of them are as satisfactory as cedar or chestnut, all things considered.

The loblollypine which grows in the southern states has many limbs and thus makes a knotty pole, which is not as pleasing in appearance as cedar. If grown in a thick stand it has too little taper to be strong at the butt.

The yellow pine as found in the western states is used in regions where it grows to some extent. The hill grown timber is the better as it is stronger and finer grained because of the slower growth. Valley grown yellow pine is knotty and not well shaped for pole purposes.

Lodgepole pine is also available in the western states. It is similar to yellow pine in respect to knots and is likely to be very slender at the butt if cut from thick stands.

All pine poles should be given a treatment of wood preservative at the butt, before being set, as their natural life is very short — less than five years in many cases.

This limitation is aggravated when the poles are set in a climate and soil which differs materially from that in which they have grown. The use of pine poles is therefore limited largely to localities where they are to be had at small expense.

Pole Defects. — All kinds of wood poles have certain natural defects which necessitate a rather careful inspection at the time of purchase or delivery.

Butt rot is common in cedar poles and is likely to occur in chestnut and other woods. It is not a serious defect unless it affects half or more of the diameter, or is so extensive as to reach up into the heart of the pole above the ground line. The presence of heart rot may be noted by an examination of the knots. If the knots show decayed centers it is probable that the heart of the tree is decayed and the pole therefore

weakened. No poles should be accepted which have rot in ring form or which are not sound at the top.

The checking which takes place in connection with the seasoning process may be sufficient to weaken the pole if it takes circular form, and involves a considerable part of the circumference of a circle. Cedar sometimes grows with a twist in the fiber. This is sufficient to affect the strength of the pole if it is so great as to make a complete turn about the axis of the pole within a length of 20 ft. or less and such poles should be rejected.

Cedar poles have scars known as "cat faces" at points where the bark of the tree has been injured. If the cat faces are large they weaken the pole and it should be rejected. It is also desirable to avoid using poles having cat faces near the top or at the ground line. Fire-killed poles should not be accepted unless it is evident that they were cut before any decaying process had affected the strength of the wood.

Steel Poles. — Where especially great strength and reliability are required, as in the yards of electrified steam railways at the ends of long spans over streams, and where appearances require something better than wood poles, the steel pole has been quite generally used.

For street lighting in residential districts where arc lamps are employed, the tubular type of pole with 3 to 4 inches butt is used. This is usually done as a matter of appearance.

The tubular pole is made in two, three or four sections, each one being welded to the larger section which overlaps it at the lower end. Three-section and four-section poles are used for heavy corners and ends where there is no possibility of guying to support the strain.

Two-section poles are made in standard sizes of 3 to 13 inches at the butt and in lengths of 22 to 30 feet inclusive. The minimum size of three-section poles is 4 inches at the butt

and they are made in lengths of 24 to 39 feet. Four-section poles are not less than 8 inches at the butt and range from 35 to 40 feet in length.

The lattice type of pole is used where lengths of more than 35 feet are required. This is usually the case in carrying transmission lines along important railroad rights of way and in cases where long spans and high poles are necessary to clear streams.

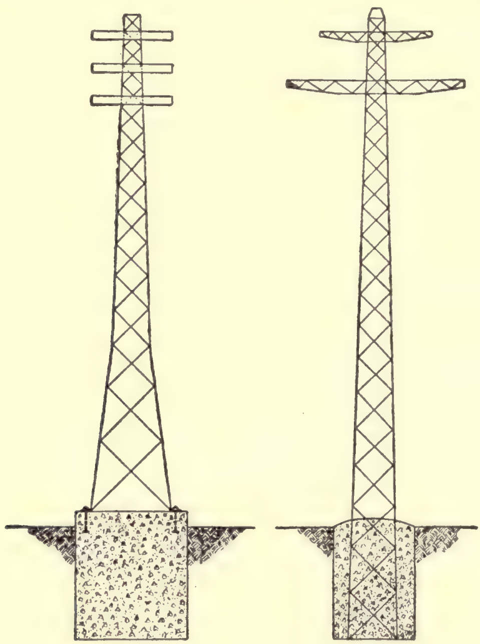


Fig. 106. Steel Poles.

The requirements of the case vary materially with local conditions, and no standard design is used except with certain patented types of poles in which various lengths are made according to a single type of construction.

The space available for foundations is to a large extent a governing consideration. Where there is ample space the

lower part of the pole may be given a greater amount of flare, thus increasing the stability and reducing the weight of the component parts of the pole. On the other hand, if the base must be made narrow, the steel must be heavier. Much depends also upon the availability of guys. Where suitable guys can be installed the pole may be much less rigid than where it must sustain the stresses by its own strength.

Two types of lattice work poles which have been used in American practice are illustrated in Fig. 106. Various modifications and extensions of these designs have been devised to fill in the gap between the steel pole used for medium high voltage transmission in built-up communities, and the elaborate tower which supports high voltage lines on a private right of way.

Reinforced Concrete Poles. — There is an increasing use of reinforced concrete poles, particularly in sections where the decay of wood is very rapid due to soil and climatic conditions. This type of pole is made either solid or hollow in form, the hollow pole having the advantage of increased strength for the same weight of material.

The solid type, which is most common in American practice, is usually built up in forms laid horizontally. The steel reinforcement should be carefully planned to take both bending and torsional strains. The cross section may be square or circular. In the square form the corners are beveled to improve the appearance and facilitate handling. The concrete must be mixed evenly and applied with care to avoid pockets and to insure every piece of reinforcing metal being thoroughly set to take its share of the strain. In short poles the top diameter may be reduced to 5 inches, but poles of the lengths in common use should be 6 inches or more at the top. The taper should be uniform above the ground line.

The metal reinforcing parts should be arranged in such a

manner as to take the stresses with as little deflection of the pole as possible. In the longer poles it is important that twisted rods or other roughened shapes be used so that the bearing surface under these will be as great as possible. This is especially important with poles which may have to sustain the tension of lines without the aid of adequate guying equipment. The longitudinal members should be well bonded laterally to prevent the tendency to buckle.

The concrete mixture which has been found best for pole structures is 1 part Portland Cement, 2 parts sand and 4 parts gravel or crushed stone. It must be well tamped and all air bubbles eliminated.

The strength of concrete increases rapidly in the first month or two after mixture, as regards compression. It is therefore desirable that concrete poles be allowed to season 30 to 60 days if possible, before they are subjected to heavy loading. Care must be used in handling while poles are new, to prevent injury to the cement. Long poles should be handled with a crane having two supports for lifting the pole.

The use of concrete poles is not desirable for general distribution purposes, where it is necessary for primary lines to be handled alive, because of the risk to linemen. Their use may be desirable however for transmission purposes where no work is attempted on lines which are alive. The concrete pole should be as strong as a wood pole for similar service and when so made is usually more expensive in first cost than the wood pole. However, its life may be materially longer and its ultimate economy must be determined from a comparison of renewal requirements.

Concrete poles are used for street lighting where a short ornamental pole of the hollow type is employed. This type of pole permits the ready use of underground cable inside the pole and is not expensive in the lengths under 25 feet, as compared with ornamental iron poles. The use of incandescent

street lighting by series and multiple systems with relatively small lighting units has greatly evidenced the field of application of the short ornamental concrete pole.

Strength of Poles. — The strength of the poles selected for general distribution must be gauged by the importance of the lines they are to carry and by the local conditions which may affect the facilities for guying.

For special cases it is sometimes important to apply theoretical calculations as a check on the strength of poles which are to carry unusual strains, and the formulas for calculating stresses should be familiar to the designer of overhead distributing lines.

The strain acting on a pole laterally at the top causes a tension in the fiber of the wood on one side of the pole and a compression on the opposite side. For a round pole the stress is

$$S = \frac{32\,PL}{3.14\,(d)^3},$$

in which P is the equivalent pull at right angles in pounds at the distance L in feet above ground and d is the diameter in feet at the ground line, or $(d)^3 = \frac{32\,PL}{3.14\,S}$.

The strain S at which the wood may safely be worked is not more than 25 to 33 per cent of its ultimate breaking strength as determined by tests of the timber in the form of poles. This high factor of safety is necessary because of the differences in the strength of different poles of the same kind, the possibility of excessive strains being placed on poles in unusual emergencies, such as the burning off of all the wires of a span and the fact that as the pole remains in service year after year, its strength at the ground line is lessened by decay, thus reducing the reserve available for an emergency.

It is found from tests that Northern cedar has an ultimate breaking strength of about 4000 pounds per square inch when tested in the form of poles. Chestnut and Western cedar are stronger, having a strength of about 6500 pounds per square inch.

In using the foregoing formula the value of S should therefore be taken at about one-third of these breaking strengths, or at 1300 pounds for Northern cedar and 2000 pounds for chestnut or Western cedar.

If a self-sustained Western cedar pole is to support a line which exerts a pull of 1000 pounds at a height of 30 feet above the ground, what should be its diameter at the ground line to safely carry the strain?

Let S be 2000, $P = 1000$, $L = 360$ inches.

$$(d)^3 = \frac{32 \times 1000 \times 360}{3.14 \times 2000} = 1764,$$

$$d = 12 \text{ inches.}$$

This would call for the use of a pole 35 feet long with a butt 12 inches at the ground line and a top diameter of 8 to 9 inches.

In city practice where streets or alleys jog or where turns are made at right angles which cannot be supported by a guy, as in the case of the line branching from Main Street to the alley east of Third Street in Fig. 107, the use of such poles is often necessary.

Wind Pressure. — The design of pole lines to withstand wind pressure in a lateral direction must be considered where sections of line are exposed. Fortunately the average city pole-line distribution is so protected by buildings and trees that it is not subject to the full force of windstorms. In exposed sections and on transmission lines supplying suburban substations, the force of the wind may be felt at times very greatly, and lines should be built accordingly. The force of

a windstorm is most apt to be an element of danger when it is exerted at right angles to the direction of a line, since there are normally no strains in this direction and no system of support is provided except for protection from storms.

The pressure of the wind blowing against a surface normal to its direction was found by Langley in a series of experiments made in 1888 to be $p = .0036\,(v)^2$, in which v is the velocity of wind in miles per hour and p is the pounds per square foot. From this it is evident that p is 20 pounds per square foot when the wind blows at 75 miles per hour, or 5 pounds at 37.5 miles per hour.

The force exerted upon poles and wires varies with the altitude as well as with the angle at which the wind strikes them, being a maximum at 90 degrees. In figuring the area of surface exposed, allowance must be made for the fact that the surfaces are cylindrical. A cylindrical surface is equivalent to two-thirds as much as a flat surface of a width equal to the diameter of the cylinder. A 40-foot pole having a top diameter of 7 inches and a butt at the ground line of 14 inches, set 6 feet in the ground, has an average diameter of 10.5 inches. The length above the ground being 34 feet, the equivalent area of pole surface exposed is $\frac{34 \times 10.5 \times 2}{12 \times 3} = 19.8$ square feet. The diameter of a No. 6 wire with triple-braid weatherproof insulation is about .3 inch. With 120-foot spans the area exposed per wire per span is

$$\frac{120 \times 12 \times .3 \times 2}{144 \times 3} = 2 \text{ square feet.}$$

As the force of the wind on the wires is exerted near the top of the pole it is more effective than the forces acting along the pole at various heights, due to the pressure of the wind.

Calculations made for a 40-foot pole indicate that the strain imposed by the action of the wind on the pole itself is approxi-

mately equal to that caused by five weatherproof wires of No. 6 A.W.G. At a velocity of 52 miles an hour, the wind pressure being about 10 pounds per square foot, the force exerted on each No. 6 wire of a 120-foot span is $10 \times 2 = 20$ pounds. The force exerted on the pole due to its own surface is equivalent to about 100 pounds applied near the top. The total force on the pole at such a wind velocity with 30 wires would therefore be $600 + 100 = 700$ pounds. Or at a wind velocity of 75 miles and a force of 20 pounds the strain on the pole would be 1400 pounds.

High velocities are attained for short intervals in nearly all parts of North America, and it is therefore advisable to provide protection for such sections of line as are exposed to the force of winds, if they carry important service. This protection is sometimes difficult to provide when lines are on public highways. It may consist of struts on the side opposite that from which winds are expected, or guys secured to anchors on the windward side.

The wind velocities recorded by the weather bureau are taken from points considerably higher from the surface than are the wires of an overhead line. Values about 75 per cent of weather bureau records may therefore be used in making calculations for a given locality.

Selection of Poles. — In the selection of poles for distributing lines, such as those shown in Fig. 107, the poles at corners and turns must be such that they will hold the wires taut for a reasonable period after they are strung. The intermediate poles should have sufficient strength to support the weight of any ordinary size of transformer and the strain of service drops.

Service drops average about 75 feet in length and may be allowed to hang with considerably more deflection than the main line wires. The unbalanced sidewise pull on a pole,

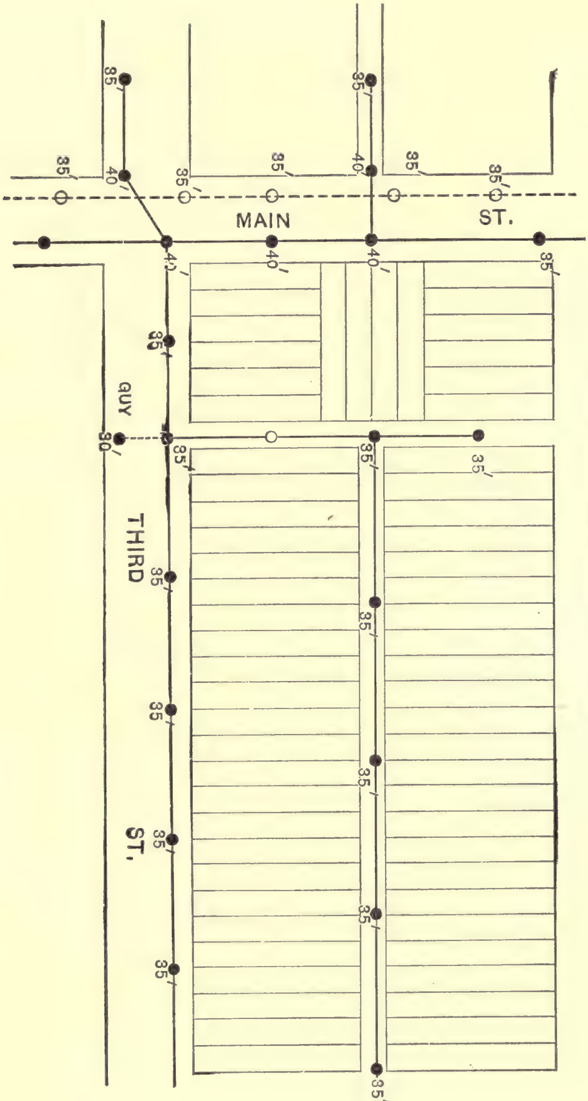


Fig. 107. Methods of Placing Poles.

therefore, does not usually exceed 300 pounds. With the services attached at a height of 30 feet, the size of the pole at the ground line should be

$$(d)^3 = \frac{32 \times 300 \times 360}{3.14 \times 1300} = 900, \text{ or } d = 9.5 \text{ inches.}$$

This corresponds to a cedar pole with a 6-inch top. However, the use of poles of this size is not permissible in sections where more than two service drops are taken from one side of any pole, as the bending of so slender a pole under the strain pulls the line out of shape. It is usual to select 7-inch-top poles for important distributing lines, 6-inch poles being used only in the scattered districts.

A deflection of more than one foot becomes noticeable in the appearance of a line and tends to place additional strain upon the pole. A strain of more than 250 to 300 pounds should therefore be balanced by a guy attachment or should be supported by a pole of heavier cross-section if guying is impracticable.

The height of the pole selected for distribution purposes must be governed by the requirements of clearance over local obstructions and by the number of cross arms to be carried on the poles. The presence of other pole lines, of trees, elevated railroad structures and buildings, requires the use of higher poles than would otherwise be necessary in some cases. Clearance over trees is especially troublesome in residence sections where trimming is not permitted. In some cases it is better to carry the wires above and in other cases below the tops of trees.

In general it is not desirable to use poles less than 30 feet long where primary lines are carried, and in built-up sections a minimum size of 35 feet is preferable. Where joint construction with another company is used it is customary to use no poles smaller than 35 feet, except for guy stubs.

It is not necessary to maintain an entire line of high poles merely to preserve the general level where a part of the line must be elevated to clear obstructions. The use of high poles is to be avoided wherever possible, in view of the cost of installation, the increased danger of failure in time of storm and the difficulty of handling transformers and service connections.

Location of Poles. — Poles should be placed in approximately equal span lengths close enough to keep the sag within safe limits and to provide a sufficient number of points at which service drops may be taken off. They should be so spaced that each block section of thoroughfare will be divided into approximately equal span lengths. The spans near self-supported corner poles should be about 75 feet if possible, in order to relieve the strain on the corner pole. The poles should be placed opposite lot lines to avoid interference with the rights of abutting property owners and to save expense of moving in case new buildings are erected. It is customary to use span lengths of 100 to 125 feet as standard.

Pole Painting. — The good appearance of poles in public thoroughfares is usually of such importance that it is considered good policy to carefully shave all poles, to remove knots and bark and then give them two coats of paint. A dark green color is very commonly used because of its harmony with foliage in residence districts.

Pole Steps. — All poles which are likely to be climbed to any extent, such as transformer poles, junction poles, poles carrying fuse boxes or other accessories, should be provided with pole steps. This expense is justified in view of the injury done the surface of the pole by the climbing spurs of linemen in the course of time. Pole steps are commonly

spaced from 30 to 32 inches apart, alternately on opposite sides of the pole.

It is the practice in most of the larger cities, where poles are used to carry the wires of two or more companies, to provide steps on all poles.

Hub Guards. — Poles which stand at the corner of a street or alley where they are subject to abrasion by the hubs of passing vehicles should be protected from injury by the attachment of hub guards to the pole at the point where abrasion of the pole is likely to occur. It is also necessary in much traveled locations to attach a similar guard about 6 feet from the ground where the box of the vehicle may scrape the poles.

The guard usually consists of a piece of plate iron one-fourth inch thick bent to the approximate curvature of a pole and secured by suitable spikes driven through holes drilled in the iron for this purpose. See Fig. 108.

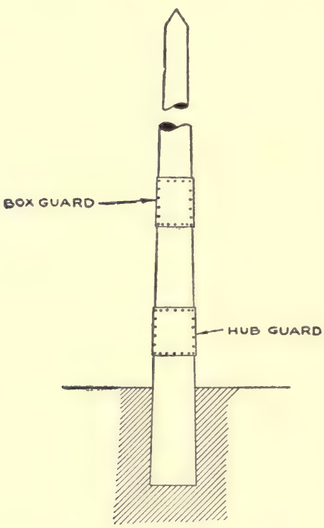


Fig. 108. Hub and Box Guard.

Gains. — The pole should be cut for the reception of the cross arms before it is erected. These incisions, called gains, shown in Fig. 109, should be about $\frac{1}{2}$ inch deep and of the necessary width to receive the arm. The distance between centers must be sufficient to give clearance for buck arms and service drops and allow a safe working space for linemen. The space usually allowed is therefore 22 to 24 inches, preferably 24 inches between gains.

Pole Setting. — The depth at which poles are set must be such that the normal strains in any direction will not pull the pole out of line. Experience has proved that the following practice is conservative for poles in a straight line:

Size pole....	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**70**
Depth......	5′	5.5′	6′	6.5′	6.5′	7′	7′	7.5′

Corner poles should be set about 6 inches deeper than the above.

The character of the soil and the diameter of the butt of the pole affect these figures in some cases.

For instance, a Western cedar pole with a small butt set in a sandy soil or swampy soil will be much more likely to pull over than a Northern cedar of the same height with a heavy butt, and more depth should be provided for it. In rocky soil where bowlders may be tamped about the pole they need not set so deep.

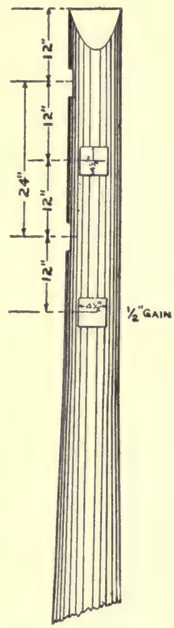


Fig. 109. Gains.

The pole should be so placed as to bring the natural bend of the pole into the line and should be set erect except at corners, where a slight rake may be given in a direction opposite the strain. Several tampers should be employed to one shoveler in filling the hole, as the thoroughness with which tamping is done while the hole is being filled is an important factor in the stability of the pole. Water may be used to settle the earth where it is available.

Where swampy soil is encountered, or in quicksand, the sinking of the hole may be accomplished by the use of a sand barrel. This consists of a sheet-iron cylinder about 30 inches in diameter and three feet long, which is separable into two

parts lengthwise. After the hole has been started the barrel is set into it, and as the earth is removed it slips down, preventing the sides of the hole from caving in. After the pole has been erected the barrel is withdrawn and removed by loosening the separable attachments.

In case the earth filling does not give sufficient stability in such soil this may often be secured by the use of a concrete filling from 6 to 10 inches thick at the base of the pole and at the ground line. This has the effect of increasing the bearing surface of the pole and will often prevent the gradual pulling out of line which takes place in such localities.

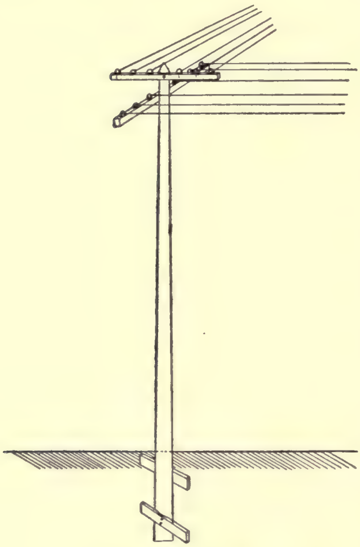


Fig. 110. Timber Supports for Corner Pole.

At corners, bends and dead ends which cannot be properly guyed for any reason, the pole carrying the strain must be self-sustained. This may be done by the use of a concrete filling as described above or by the use of timbers secured to the pole as shown in Fig. 110. Poles having top diameters of 8 to 10 inches should be used for this class of work. The timber method requires the excavation of a rather large hole, but it provides an ample bearing surface and is usually less expensive than the concrete method. The timbers should be about four feet long and 8 to 10 inches in width. They may be of 3-inch plank or a section of an old pole. The upper should be at least 6 inches below the surface in order to preserve the timber.

Guying.— At all points where the direction of a line changes, the tension of the wire should be supported if possible by guying equipment of such strength and design as will insure the permanent stability of the pole line and its accessory equipment.

Guy wires are secured at the ground in various ways, depending upon the space available and the clearance required.

Where there is nothing to prevent the guy wire being brought down to the ground near the poles the guy cable may be

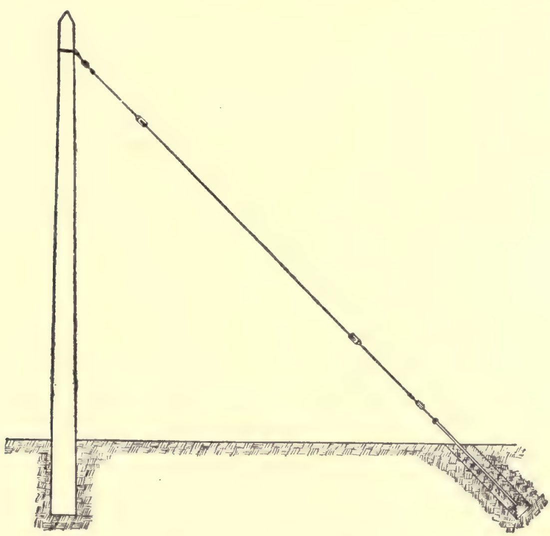


Fig. 111. Anchor Guy.

secured to an anchor as shown in Fig. 111. The anchor is made of timber such as a piece of a pole 4 feet long, or it may be a patent anchor of some form. The use of the timber requires a large excavation, while most of the patent anchors are driven or screwed in without digging a hole. The use of a timber is therefore somewhat more expensive in cases where

the nature of the soil is such as to permit the installation of the patent anchors.

Where the soil is rocky or where obstructions exist, excavation is necessary and the timber method is likely to be preferable.

Where trees of sufficient size to hold lines without swaying are available they may be used sometimes as anchors. Other fixed objects, such as large rocks and buildings, may also be used in special cases. The location of corner poles on public thoroughfares is often such that guys cannot be run directly

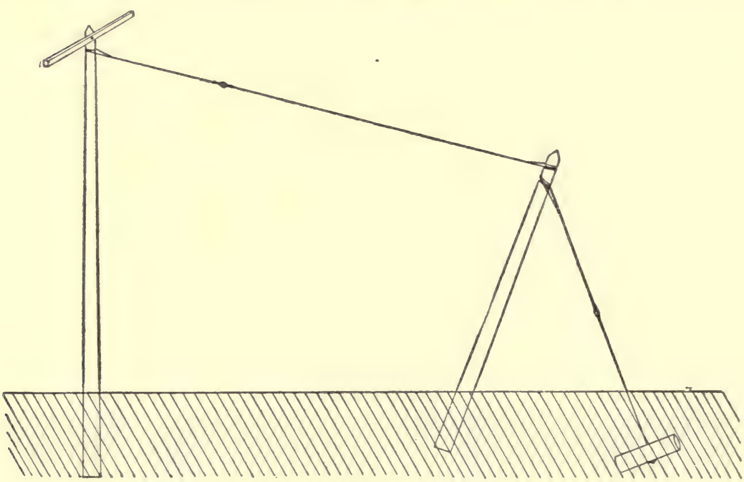


Fig. 112. Anchored Stub Guy.

to anchors without interfering with traffic. Under such circumstances the guy must be run to a pole known as a stub, where it is attached at such a height as to permit free passage under it. It is usually required that guys over roadways should clear the crown of the road about 18 feet, and those over pathways should clear at least 12 feet.

This class of attachment is illustrated in Fig. 112.

The stub is sometimes made self-supporting where the use

of an anchor is not practicable or where the height of the stub is not over 15 feet.

On lines which carry three or more cross arms it is important to attach guys on the pole at two points so that the strain will be distributed and the pole will not be gradually bent out of shape.

Where side arm construction is used it is necessary to support the cross arms as well as the pole at corners and ends by means of guys attached to eyebolts in the arm.

At heavy corners which are guyed to stubs or anchors and at self-sustained corners a "head" guy may be used to good advantage. It is run from the base of the corner or end pole to the upper part of the next pole in the line. If the line wires are well secured at the poles next to the corner the tension in the corner spans may be reduced, thus relieving the strain on the corner pole.

In straightaway lines the head guy is used to limit the extent of damage in case several poles go over in a wind storm. The head guys on long lines are placed at intervals of about 20 poles. Similarly where a long span exists which is likely to become crossed and burn open, head guys should be maintained at each side to support the line each way in such an emergency.

A typical use of the head guy on a terminal pole is illustrated in Fig. 113.

Generally speaking the head guy is a useful means of securing reserve or auxiliary guying for the other forms of guys. Terminal poles, corner poles and jogs in the line may often be head-guyed to advantage.

Guy Cables. — Steel wire or cable is generally employed for guying purposes because of its high tensile strength. It should always be galvanized, since the value of the guy is largely dependent upon its durability and reliability, and plain steel wire is subject to rapid corrosion which steadily weakens it.

The stiffness of steel wire is such that it is very difficult to bend it in securing the ends in sizes above No. 8 B.W.G. without impairing its strength. It is therefore used most generally in the stranded forms for guying purposes.

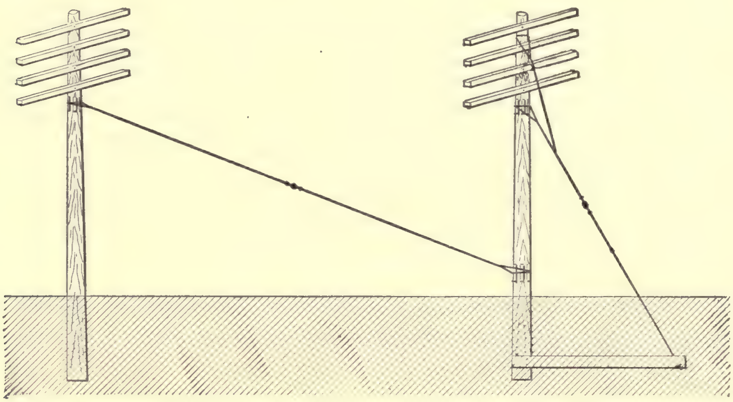


Fig. 113. Head Guy at Terminal Poles.

Two sizes of stranded cable are commonly used for guying work, viz.: one-fourth inch having an ultimate tensile strength of 2300 lbs. and three-eighths inch having a strength of 5000 lbs. The 2300-lb. wire is used for the support of lines having one cross arm only and for guying single arms in side arm construction. Larger lines and heavier strains are commonly carried by the 5000 lb. size.

The properties of standard steel strand are as follows:

Area, square inches.	Diameter, inches.	Weight per 1000 ft.	Ultimate strength, pounds.
.144	$\frac{1}{2}$	510	8500
.121	$\frac{7}{16}$	416	6500
.080	$\frac{3}{8}$	295	5000
.064	$\frac{5}{16}$	210	3800
.035	$\frac{1}{4}$	125	2300

Three special grades of galvanized steel strand are also made for special purposes. The Siemens-Martin strand is about 40 per cent stronger than the standard strand. High Strength or Crucible Steel strand is more than twice as strong as standard while Extra High Strength Plow Steel strand is about three times as strong.

These are used only where great strength is required with a minimum weight, as in catenary construction or in making very long spans.

Calculation of Size of Guy Cable. — The pull on a pole due to the tension of the wires having been calculated from the size of the wires, their deflection and span lengths, the tension on the guy wire is equal to the sum of the tension of all the line wires multiplied by the length of the guy wire and divided by the horizontal distance from the pole to the point where the guy wire is attached to the anchor or stub.

Having calculated the tension in any case the size of guy cables should be such that the strain will be from $\frac{1}{4}$ to $\frac{1}{5}$ the ultimate breaking strength of the cable.

For instance, with a line carrying 18 wires at a tension of 150 pounds each, supported by a guy cable 40 feet long, with the anchor attachment 30 feet back from the pole, what size of guy cable should be used? The total line wire tension is 2700 pounds, and the guy cable tension is therefore $\frac{2700 \times 40}{30}$ $= 3600$ pounds. This would require the strength of two 5000-lb. cables to support the strain.

In case the anchor were but 12 feet back from the pole, the cable would be about 36 feet long, and the tension on the guy would be $\frac{2700 \times 36}{12} = 8100$ pounds.

This would necessitate the use of two 5000-lb. cables attached to the anchor, and a head guy of $\frac{3}{8}$-inch cable to the

first pole back from the terminal pole. The head guy, acting at a more favorable angle, could be adjusted to carry a part of the strain. An anchor should not be placed nearer to a pole than one-quarter the height of the guy attachment on the pole.

Attachment of Guys. — In making attachment of a guy cable to a pole or stub it is given two turns about the pole and the end brought back and well secured. The smaller

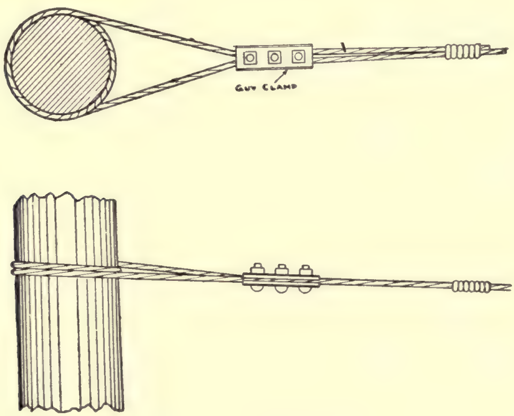


Fig. 114. Guy Clamps.

sizes may be secured at the ends by wrapping, but the larger sizes are preferably fastened by means of clamps. When an anchor having an eye at the upper end is used the cable should be protected by a thimble to avoid too sharp a bend at the point where all the strain is carried.

The method of applying clamps which are bolted and of securing the end of the guy cable is illustrated in Fig. 114.

When guys are attached to a tree, the tree should be protected by the use of suitable blocks between the cable and the tree to prevent cutting into the bark. It is also desirable with

heavy guys to put protecting strips under them when wrapping the cable about the pole. This is not so necessary with chestnut and other timber having hard sapwood. Strips of galvanized plate iron about 2 inches wide are commonly used for this purpose.

Strain Insulators. — The proximity of guy cables to primary wires affords opportunity for leakage in wet weather and renders

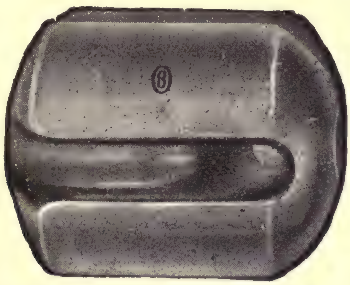


Fig. 115. Porcelain Guy Insulator.

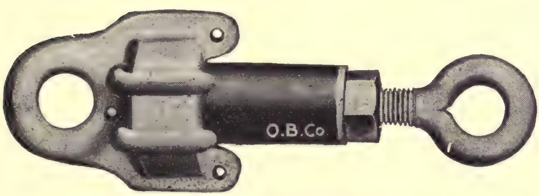


Fig. 116. 600-volt Strain Insulator.

them subject to accidental crosses with live conductors at times. It is therefore important that guy cables be equipped with strain insulators attached not less than 8 feet from the ground. This precaution is advisable for the protection of the public and of linemen, whose safety is endangered by the presence of grounded guy cables near live wires on which they are working. It is therefore customary to keep guy cables above ground as much as possible and to sectionalize them by the use of two strain insulators of the type shown in Fig. 115.

The strain insulators are put in about six feet from each end.

The guying equipment should be installed before the wire is strung so that when the tension is applied the corner poles may be pulled up to their normal position.

In supporting the strain of high-tension lines up to 13,200 volts it is customary to employ porcelain strain insulators of the same type, but having larger leakage surfaces.

With heavy low-tension feeders the strain is carried by attaching a strain insulator of the type shown in Fig. 116 directly to the conductor and using a separate guy wire for each conductor back to a guy pole.

CHAPTER X.

OVERHEAD CONSTRUCTION.

LINES AND ACCESSORIES.

Cross Arms. — In the selection of wood for cross arms for distribution work the physical characteristics of the wood must be carefully considered. Longleaf Southern pine and Douglas fir are the best woods, because of their straight grain, high tensile strength and durability. The chief cause of deterioration in cross arms is the alternate action of the sun and rain, which tends to open up cracks on the upper side, allowing water to soak into the wood and creating conditions which are favorable to processes of decay. It is therefore important that the top surface of the cross arms be rounded off so that the water will run off easily.

The timber should be thoroughly air-dried or kiln-dried before it is worked up as the shrinkage of pin holes in arms made when the wood is green is sufficient to seriously interfere with the fitting of the arm with pins.

There should not be over 15 per cent of sapwood in pine or fir arms and this should be on the side or top. The grain should be straight and there should be no knots of such size as to weaken the arm. This requires that there be no knots over $\frac{3}{4}$ inch in diameter in the standard arm. There should be no checks over 3 inches long, no loose hearts, and no worm-eaten or otherwise unsound portions of the cross arm. These requirements are essential to the safety of men working on the line, as well as to the security of the service rendered.

The cross-section should be of such shape and area that the arm will bear the weight of a lineman, in addition to that of

the wires, without danger of breaking. This demands a good factor of safety to provide for proper strength after the arm has become weakened by partial decay. Experience indicates that a cross-section $3\frac{1}{2}$ inches wide by $4\frac{1}{2}$ inches high is ample for the average requirements of distributing lines.

The appearance of a distributing line is best if a uniform length of cross arm is used. In suburban districts main lines are commonly of six-pin arms with four-pin arms on the distributing lines.

In city work where both light and power secondaries must be carried on the same arm, it is usually found necessary to use six-pin arms for distributing lines with eight-pin arms on lines carrying many wires.

Where lines are occupied jointly with other companies it is desirable that arms of approximately equal length be used by each company.

The spacing of pins should be suited to the voltage of distribution, should provide a safe working space for linemen and should take into account the normal sag of the wires. Under the usual working conditions of distributing lines it is not safe to attempt to use spacings for primary wires less than 12 inches; 14 to 15 inches between centers is preferable. In general, the wider spacings are common on four-pin arms and the narrower on eight-pin. The spacing of pins next to the pole must be such that sufficient room is left for linemen to get up through the lower wires safely to work on the upper arms, at least 24 inches being required between pole pins and 30 inches being preferable. The dimensions and spacings of standard cross arms are shown in Fig. 117.

The dimensions shown are those recommended by the National Electric Light Association. They are representative of average practice, minor variations being found in various parts of the country.

In the attachment of cross arms, the arm should be placed

on the side of the pole away from the heaviest strain. In a straight line, the arms should be put face to face and back to back in alternate spans. The face of the pole is the side on which the arm is mounted.

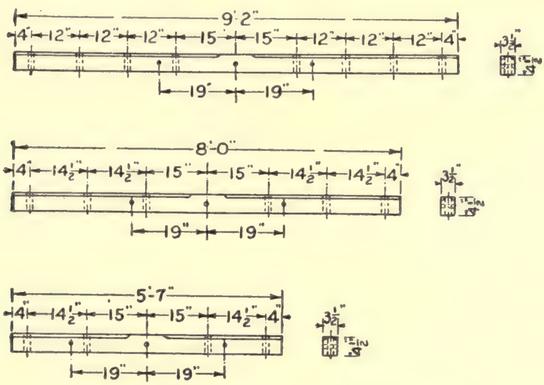


Fig. 117. Dimensions of Cross Arms.

Side Arms. — In cities where the system of alleys is used wherever possible for distributing lines, the narrowness of the roadway is such that the poles must be set close to the property lines, and the presence of buildings makes it necessary to keep the cross arms from overhanging the property. This necessitates the use of side arms, or alley arms, as they are commonly known, as shown in Fig. 118. The unbalanced weight on the pole caused by such construction is not serious and is readily compensated for by setting the pole with a slight rake toward the property line. The weight of the equipment when attached brings the pole up straight, on ordinary distributing lines.

Double Arming. — At corners, terminals and other points where there is an unusual strain, the poles should be fitted with a double arm equipment so that the strain will be carried by more than one support.

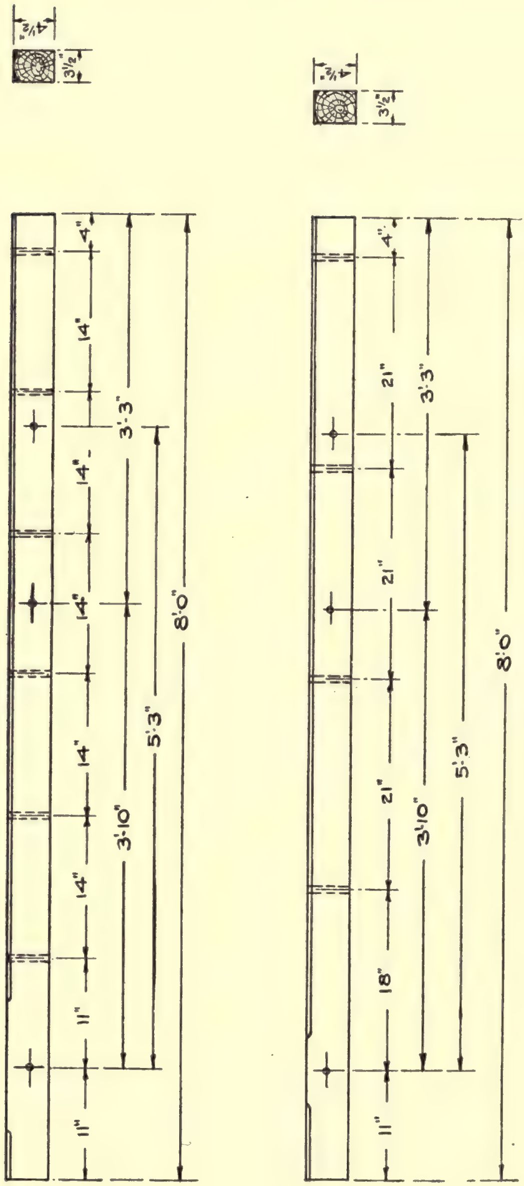


Fig. 118. Dimensions of Side Arms.

The arms should be bolted together at the ends with suitable spreaders to fill in the space between them and make a solid structure. This may be done by the use of a block of wood or by spreader bolts having nuts which clamp the arms on both sides, as shown in Fig. 119. It is usual to use $\frac{5}{8}$-inch bolts with either type of spreader, to bind the arms together. Suitable washers should be used to give proper bearing surface between nuts and wood.

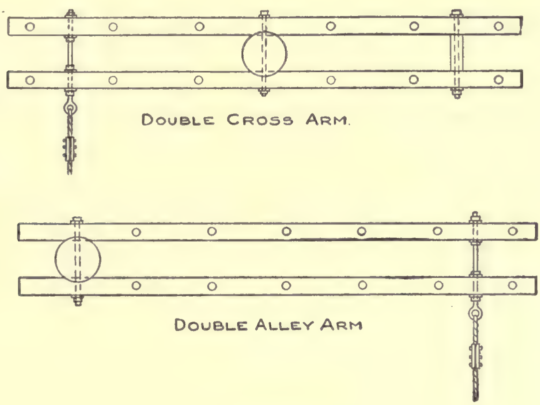


Fig. 119.

The double arm bolt may be provided with an eyelet as shown in Fig. 119 instead of one of the nuts. This makes a convenient point of attachment for an arm guy cable on terminal poles with side arms.

An eyebolt is required for this purpose where a single arm is guyed.

Washers of square plate $\frac{3}{16}$ inch thick and 2 by 2 inches are used on cross arm bolts. Circular washers $1\frac{1}{2}$ inches in diameter are used with carriage bolts on braces.

It is desirable for clearance, in case there are more than two cross arms on the poles, to double arm the first pole away from

the corner in each direction and support the strain by means of head guys as shown in Fig. 120.

Arm Bolts. — Arms may be fastened to the pole by bolts or lag screws. The use of bolts is preferable, as the fastening of the arm becomes insecure in the course of time, due to decay

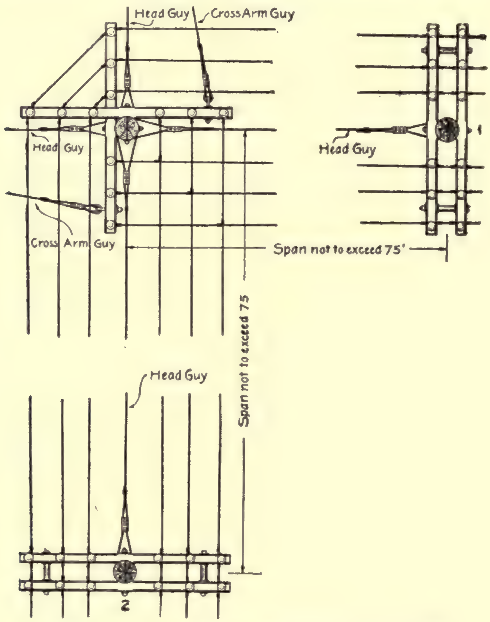


Fig. 120. Double Cross Arms at Corners.

of the pole around the threads of the lag screw. The bolt is fitted with a nut and washer on both ends, to give a firm and durable seat for the nut. The bolt should be $\frac{5}{8}$ inch in diameter and from 12 to 16 inches long, depending upon the diameter of the pole.

Arm Braces. — In order to hold the cross arm firmly in a horizontal position, braces must be provided. These are

usually of strap iron about $\frac{1}{4}$ inch by 1 inch by 26 inches to 30 inches long. The brace is placed at an angle of about 45 degrees with the pole and is attached by means of lag screws to the pole and by stove bolts through the cross arms.

Side arms must be supported at a point farther out from the pole than center arms and it is therefore usual to use a brace of angle iron such as that shown in Fig. 121. This is rigid enough to bear the weight of a lineman on the step

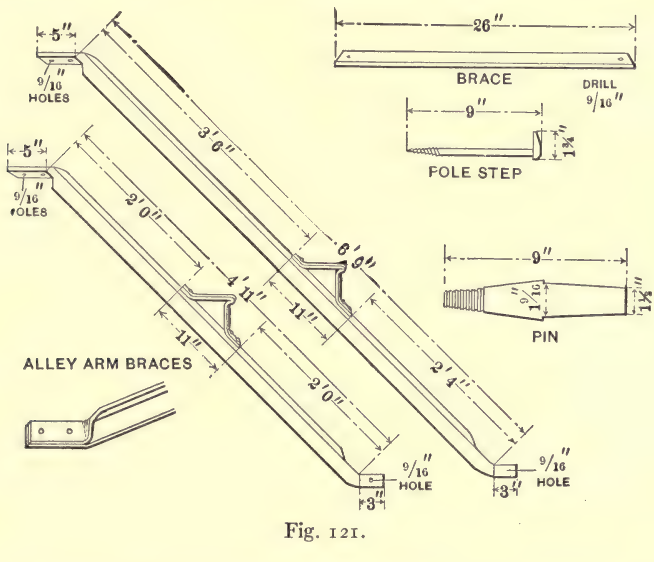


Fig. 121.

while working on wires at the outer end of the arm. This brace is used only on the lower arm where there are several arms on a pole.

The upper arms must be supported by braces of $\frac{1}{4}$ inch by 1 inch by 26 inches strap iron run vertically from the outer end of the angle iron brace.

Pins. — Pins of wood are preferred for distribution work on account of their low cost and insulating qualities. Locust,

elm, oak and other woods are common, but locust is superior to all in strength and durability. Tests made on pins of the sizes shown in Fig. 95 gave an ultimate breaking strength of about 1200 pounds for oak, 1400 pounds for elm and 1600 pounds for locust. These figures represent the pull in pounds applied on a deep-groove double-petticoat insulator mounted in its normal position on the pin, and therefore indicate the breaking strength of the pin under working conditions. A factor of safety of 4 to 6 is advisable, and care must be used in selecting pins free from knots and dry rot and having straight grain.

Where wires of No. 2 and smaller are dead-ended or carried around a corner it is customary to distribute the strain between two pins by using double-arm construction. With heavier cables it is not desirable to attempt to support the strain by a pin, but it is usual in such cases to insert a strain insulator in the line near the pole and take the strain more directly on the guy cable.

Pins should be coated with white lead before being put into the pin holes and should then be secured by a sixpenny galvanized nail. It is usually better economy to fill all pin holes with pins in the shop before the arms are sent out for use. Iron pins are commonly used for transmission lines where the size of the insulator necessitates a pin so long that wooden pins of the ordinary type are not adequate.

The cemented type of pin is made in two forms, solid and with detachable thimble. The solid type must be cemented to the insulator before it is mounted on the arm, and after delivery in the field. The difficulties of handling such work properly in the field led to the development of the detachable thimble. This may be cemented in the insulator at the factory and screwed to the iron pin on the cross arm, thus mounting the insulator as readily as it is done with wood pins. This type of pin also greatly facilitates the replacement of defective insulators.

Iron pins are secured to the cross arm by nuts and washers on the under side of the arm, as shown in Fig. 122. There are also certain types which are made in the form of a clamp bolted around the arm, and not passing through it.

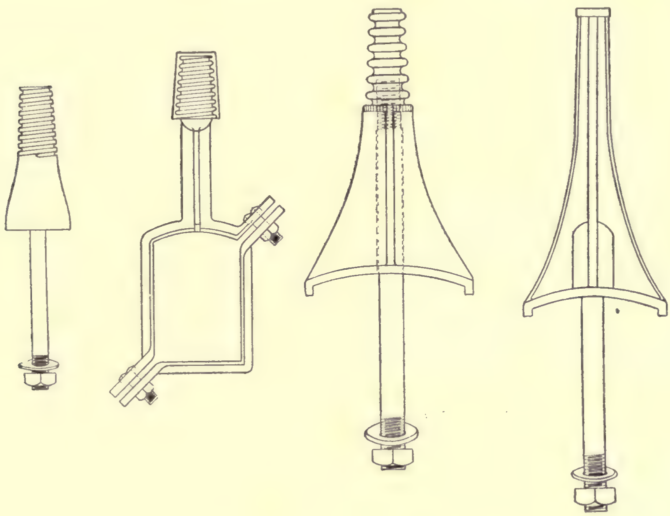


Fig. 122. Iron Pins.

Iron pins are used quite generally for the voltages above 10,000, up to about 40,000 volts, above which the suspension type of insulator is generally considered preferable.

The insulator is secured to an iron pin by threads as with the wood pin, or by cementing. In the threaded type, provision must be made for expansion to guard against cracking the insulator. This is done in various ways. In the smaller sizes, a threaded wood thimble is mounted on the iron rod which forms the shank of the pin. In other forms, the threaded portion is slotted and a piece of felt serves as a cushion in the slot. The threads are made in the form of a spiral spring in another type. This has sufficient flexibility to take up the strains of contraction and expansion.

Insulators. — The most common type of insulator in distribution practice is that known as the deep-groove double-petticoat insulator of glass or porcelain shown in Fig. 123. The dimensions of this insulator are sufficient to carry circuits operating at potentials up to 5000 volts safely with standard wooden pins. The groove is ample for any size of weatherproof wire up to 0000. The line wire is secured to the insulator by a tie wire laid in the groove and twisted around the line wire several times at each side of the insulator. The point of support is relatively low and the side strain on the pin is therefore reduced to a minimum.

Fig. 123. 2300-volt Insulator.

The double petticoat is ample protection from leakage of electricity during stormy weather.

The glass insulator is most commonly used for distribution purposes at voltages under 5000. In some cases porcelain insulators are used for primary wires with glass for secondary mains. Others have adopted porcelain insulators having different colored glazing as a means of readily identifying circuits of different classes. This is said to be found effective as a safety precaution where series lighting circuits, power circuits and general lighting circuits are carried on the same poles.

Manufacture. — The manufacture of porcelain insulators is carried by two processes known as the *wet* and the *dry*. The methods vary also in accordance with the character of the clays which are used and each manufacturer must adapt his processes to the clays which are best suited to the majority

of his product. Clays from different sources vary in their electrical, mechanical and chemical characteristics and it is often necessary to use mixtures in order to secure the best product.

The mixture must be thoroughly made in order to produce a uniform quality of porcelain.

In making porcelain by the wet process, the clay is brought to a state of wetness sufficient to make it plastic. It is worked into a mold, which forms the outer shape of the piece while a central plunger forms the inner side. The plunger or mold is rotated to secure a symmetrical piece. After being formed, the piece is set aside to dry until it is strong enough to be removed from the mold without danger of distortion. It is then left until quite thoroughly dried, when it is put into a lathe and smoothed up ready for firing and glazing. The parts which are to be cemented are turned sufficiently to insure an accurate fit.

By the dry process, the clay is used in the form of a dampened powder made by pulverizing the dried mass of clay left after the mixing process. This pulverized clay is pressed into steel molds under heavy pressure. The molded piece is set aside to be thoroughly dried before firing and glazing. The steel molds are so accurately made that little finishing work is needed before the glaze is applied.

The glazing is applied by dipping the molded piece of clay into a solution which covers all parts of the clay which are to be glazed. The clay is then fired at a carefully regulated heat for about 48 hours after which it is allowed to slowly cool before the kiln is opened for the removal of the porcelain.

Wet process porcelain is used for high tension insulators because of its mechanical and electrical strength, while the dry process is preferred for the complicated shapes used in many ways at lower voltages.

Insulators for voltages of over 20,000 are made in two or more pieces, as shown in Figs. 124 to 126, which illustrate common designs for use at 20,000, 33,000 and 44,000 volts, respectively.

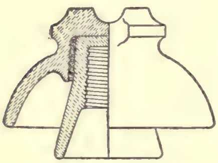


Fig. 124. 20,000-volt.

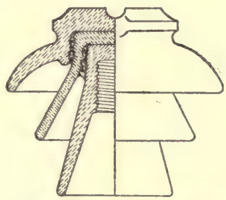


Fig. 125. 33,000-volt.

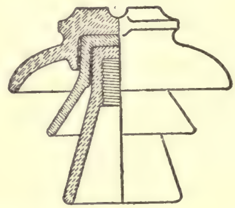


Fig. 126. 44,000-volt.

Each petticoat of such insulators is formed and fired separately in order to insure greater dielectric strength and avoid the checking which takes place in thick pieces of porcelain during the firing process.

These pieces are then assembled by the use of a suitable cement. Pure Portland cement is quite commonly used and is in most respects the best. Sulphur is strong and a good insulator but in case of heat from an arc, easily melts and mechanical failure results. Condensite, a substance derived by chemical process, is excellent for the purpose, from the standpoint of electrical and mechanical strength, but is rather expensive.

It is important that the design of an insulator take into account both electrical and mechanical stresses. The shape of the petticoats must be such as to permit a discharge to flash over before it will puncture, if the number of insulator failures is to be kept at a minimum. It is usual to make the proportions such that the puncture strength is about 1.3 to 1.5 times the flash-over voltage.

Mechanically the insulator must be able to support the tension and weight of the line without crumbling and with sufficient factor of safety to prevent early failures. These features

of design are largely matters of experiment and practical operating experience.

Such problems are more apt to be troublesome with tower lines having long spans and heavy conductors, than with standard lines on highways.

Wire. — The wire used for overhead distribution work in cities should be of annealed copper and covered with three fibrous braids impregnated with weatherproof compounds.

The size of wires is in general determined by the conditions of load, distance, etc., but in overhead work the mechanical strength must be adequate and it is therefore not safe to use wire smaller than No. 6 for primary lines. It is also common practice to extend this rule to low-tension lines, though No. 8 is sometimes used for short secondary lines. No. 8 and No. 10 are used for service drops to small consumers quite generally.

Wire Stringing. — In erecting wire it is usual to string the conductors by a rope and a team of horses over the cross arms for a distance of several spans of line. When in place one end is secured and tension applied to the wires separately by the use of block and tackle. When the tension has been correctly adjusted, linemen stationed at several points apply the tie wires, thus securing the line to the insulators. The remaining wires are similarly drawn up, care being taken to get the tension on all wires about the same. The tension varies with the size of the wire and with the deflection which is considered permissible. It should be made sufficient to prevent too much sag in the spans and yet must not be so great as to unduly strain the wire and the guying equipment which supports it.

Tie Wires. — Line wires are secured to the insulator by means of tie wires or with heavy lines and long spans by means

of clamps. Tie wires are used almost exclusively with distributing circuits as they are sufficient to withstand the usual loads found in such work. With weatherproof or other insulated wire, the tie wires should be insulated in order to prevent cutting through the line wire insulation. Annealed wire should be used to insure a tight wrap and the size used for various sizes of line wire should be as follows:

No. 6 tie wire for No. 6 or No. 4 line wire.
No. 4 tie wire for No. 2 or No. 1 line wire.
No. 2 tie wire for No. 0 or No. 4–0 line wire.

In straight runs the ties on the pole pins should be applied so that the wires will be on the side of insulator away from the pole. On the other pins, the wire should be on the side nearest the pole. At corners and bends all wires should be

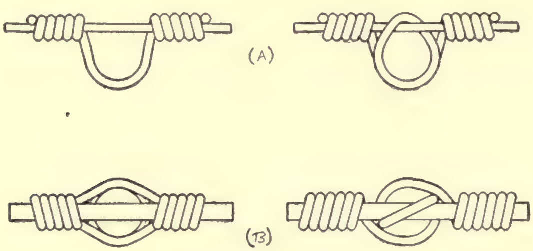


Fig. 127. Ties.

behind the insulator, that is, on the side opposite the direction of pull. The common method of applying tie wires to insulators having side grooves is illustrated in Fig. 127(*A*). For the larger sizes of conductors, where the groove is on top of the insulator, the tie shown in Fig. 127(*B*) is commonly used.

For heavy transmission lines with long spans it is often considered preferable to attach the line wire to the top of the insulator by the use of a clamp such as that shown in Fig. 128.

This device is also useful at the ends of long spans or at other points of extra strain.

Joints and Taps. — Joints in line conductors should be carefully made to support the tension of the line and to give good electrical conductivity. They must be soldered to preserve their conductivity and should be taped to an amount equivalent to the insulation of the wire to protect linemen.

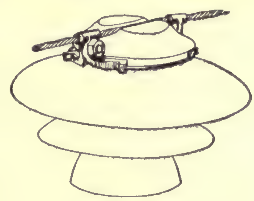


Fig. 128.

Taps must be treated in a similar manner.

With stranded cables a neatly interwoven joint is essential to carry the load.

Where possible, joints should be made at points where the tension is a minimum.

Calculation of Tension and Sag. — The theoretical curve formed by a wire supported under tension as in pole work is known as a catenary. The equation of this curve is based on the assumption that the wire is inextensible and perfectly flexible. This is, of course, not strictly true of insulated copper wire, and it is therefore found sufficiently accurate for all practical purposes to use the approximate formula by Rankine and others as follows:

$$T = \frac{(L)^2 w}{8S},$$

in which T is the wire tension in pounds, L is the length of the span in feet, w is the weight of one foot of conductor and insulation, and S is the sag or deflection in feet.

To illustrate, assume a No. 6 weatherproof wire carried on poles 100 feet apart, with a sag of 1 foot; what is the tension on the wire? The weight of one foot of No. 6 wire being

about 0.112 pound, $T = \frac{100 \times 100 \times .112}{8 \times 1} = 140$ pounds. If the spans were 141 feet, the strain would be doubled, and at 200 feet they would have to be quadrupled in order to keep the sag at one foot. If the tension is the same on several spans of different lengths, the deflection will be different in each span. In practical work this is usually the case, as the tension is usually the same throughout any section of line unless special provisions are made for guying certain spans of unusual length so as to increase the tension.

With a deflection of one foot in a 100-foot span and a spacing of 14 inches between wires, there is very little danger of wires swinging together in a high wind. With a sag of more than two feet in a 141-foot span, however, there is great danger as the wires are slack enough to allow them to swing out of synchronism in a gusty wind.

The sag of any span when the tension is known is found by interchanging T and S in the foregoing formula so that it reads $S = \frac{(L)^2 w}{8T}$. In the case of a 0000 wire in a 141-foot span under 1025 pounds tension,

$$S = \frac{141 \times 141 \times .82}{8 \times 1025} = 2 \text{ feet.}$$

The maximum tension in a line is limited by the strength of the wire and its supports. The ultimate breaking strength of annealed copper wire is about 34,000 pounds per square inch, but the working strain should not be over one-quarter of this. If pulled up too tight the wire stretches, increasing the sag and diminishing its cross-section.

For No. 6 wire, which has an area of .0206 square inch, the ultimate breaking strength is about 700 pounds. The safe working strain is therefore about 175 pounds, which gives a 14-inch sag in a 125-foot span. The safe working strength of

0000 wire, which has an area of .1662 square inch, is found in a similar way to be 1400 pounds, which gives about 15 inches sag in a 125-foot span.

With hard-drawn wire the ultimate tensile strength is about 60,000 pounds. Such wire is left in the hardened condition in which it comes from the wire-drawing dies, which gives it greater strength and stiffness. The wire, however, must not be scratched or kinked in handling, as any injury to the surface reduces the strength of the wire at that point to the strength of annealed wire. The same is, of course, true if it is heated for soldering. Hard-drawn wire is therefore not adapted to general distribution work where taps must be made with soldered connections at frequent intervals. For transmission lines and series arc circuits it has advantages which are generally recognized and made use of.

The sag and tension of weatherproof and bare, hard-drawn wire may be readily determined from the figures in the following table for various sizes of wire.

ANNEALED WEATHERPROOF WIRE, 100-FOOT SPAN.

B. & S. G.	10	8	6	4	2	1	0	2/0	3/0	4/0
T at 1 ft. sag	62	92	140	204	318	390	486	607	767	942
S at 100 lbs. tension	.62	.92	1.40	2.04	3.18	3.9	4.86	6.07	7.67	9.42
Weight wire per ft.	50	74	112	163	254	312	388	486	614	754
Breaking stress	283	440	700	1114	1772	2234	2818	3553	4480	5650

HARD-DRAWN BARE WIRE, 100-FOOT SPAN.

T at 1 ft. sag	39.3	62	99	157	161	202	400	505	636	800
S at 100 lbs. tension	.393	.62	.99	1.57	1.61	2.02	4.0	5.05	6.36	.80
Weight wire per ft.	31.4	50	79.5	126	201	253	320	403	508	640
Breaking stress	500	778	1237	1967	3127	3943	4973	6271	7907	9971

The tension at any other sag, or the sag at any other tension, or the sag or tension in any other length of span, may be readily found from the above table as follows:

The tension at any other sag is $T' = \frac{T}{S}$, in which S is the sag in feet at which the tension is desired and T is the value in the above table in pounds.

For illustration, what is the tension in a 100-foot span of No. 0 weatherproof wire at a deflection of 2 feet?

$$T' = \frac{T}{S} = \frac{486}{2} = 243 \text{ pounds.}$$

Similarly the sag at any other tension is $S' = \frac{S \times 100}{T}$, in which T is the assumed tension and S is the value of sag at 100 pounds in the above table. With No. 0 weatherproof wire the sag at 300 pounds is

$$S' = \frac{S \times 100}{T} = \frac{4.86 \times 100}{300} = 1.62 \text{ feet.}$$

With spans of other lengths the sag or tension varies in proportion to the square of the length of the assumed span.

That is, $S' = \left(\frac{L'}{100}\right)^2 S$ and $T' = \left(\frac{L'}{100}\right)^2 T$.

With No. 4/0 bare wire for instance the tension with a span of 150 feet at 1 foot sag would be $T' = \left(\frac{L'}{100}\right)^2 T = \left(\frac{150}{100}\right)^2 \times 800 = 1800$ pounds. Or if the tension of the line were 100 lbs. in all the spans, the sag in a 150-foot span of bare No. 4/0 wire would be $S' = \left(\frac{L'}{100}\right)^2 S = \left(\frac{150}{100}\right)^2 \times 8 =$ 18 feet.

The foregoing table may be used in the solution of practical problems as follows:

A line of No. 2 weatherproof wire is to be strung on poles

with spans of 110, 150 and 200 feet at various points. What deflection will result if the wire is pulled up to a tension of 300 pounds on all spans?

The sag at 300 pounds on a 100-foot span is

$$S' = \frac{3.18 \times 100}{300} = 1.06 \text{ feet.}$$

On 110-foot spans, $S' = 1.1 \times 1.1 \times 1.06 = 1.28$ feet.

On 150-foot spans, $S' = 1.5 \times 1.5 \times 1.06 = 2.38$ feet.

On 200-foot spans, $S' = 2 \times 2 \times 1.06 = 4.24$ feet.

If 4.24 feet is considered more deflection than is safe on the 200-foot spans, what tension must be used to reduce this to 2.5 feet?

$$T' = 300 \times \frac{4.24}{2.5} = 510 \text{ pounds.}$$

Expansion and Contraction. — The changes in the sag of lines due to the expansion and contraction of the wires under varying temperatures are of much importance in the erection of the conductors. Lines erected during the summer months are found drawn very tight during the winter months, while those erected during winter months are apt to be too slack during the summer. Allowance should therefore be made for the temperature at the time the work is done.

The length of the wire in any span may be calculated from the approximate formula

$$L' = L + \frac{8\,(S)^2}{3\,L},$$

in which L is the length of span in feet and S is the sag in feet. With a 100-foot span of 1 foot sag,

$$L' = 100 + \frac{8 \times 1}{3 \times 100} = 100.0266 \text{ feet.}$$

That is, the wire is .0266 foot or .32 inch longer than the span. Likewise, if the length of wire is known, the sag is

$$S = \sqrt{\frac{3L(L' - L)}{8}}.$$

For instance, if a wire should slip on the insulator so as to add .48 inch or .04 foot to the length of wire in the above span, the sag would be increased to

$$S = \sqrt{\frac{3 \times 100}{8}(100.0666 - 100)} = 1.88 \text{ feet, or } 19 \text{ inches.}$$

The same condition would result if the pole were pulled over so as to shorten the span .48 inch.

The length of wire in a span varies in proportion to the coefficient of expansion and the range of temperature. $W' = W(1 + at)$, in which a is the coefficient of expansion, t is the range of temperature in degrees Fahrenheit, and W is the length of wire at the lower temperature. When the length of wire at the higher temperature is known and the contraction is to be computed instead of the expansion, the formula is $W = \frac{W'}{1 + at}$, in which W' is the known length at the higher temperature.

The coefficient of expansion of copper wire is $a = .000096$ per degree rise Fahrenheit. This is subject to some variation under the conditions of practical operation due to stretching which affect the accuracy of calculations for the wider ranges of temperature. These are not capable of exact determination in a form which is applicable to general distribution work. It is therefore found most practical to establish sag tables based on actual experience. The following table has been adopted as recommended practice by the National Electric Light Association.

SAG IN WIRE ERECTED AT VARIOUS TEMPERATURES, INCHES

Length of span.	Temperature, degrees Fahrenheit.							
	20°	30°	40°	50°	60°	70°	80°	100°
Ft.								
60	4	5	5	6	6	7	8	9
80	7	9	10	11	12	13	14	15
90	10	12	13	14	15	16	17	19
100	14	15	16	18	19	20	21	23
110	18	19	21	22	23	24	25	27
120	22	24	25	26	27	28	30	32
130	27	29	30	31	32	33	35	37

These figures are based on the supposition of structures which have some elasticity at the extremes of temperature and with a factor of safety of about 2 at the lower temperatures. This may be lowered somewhat by strains at temperatures lower than 0° F., but experience has shown that distribution lines erected on the basis of the above table are not subject to excessive breakage during severe cold weather.

In long spans which are occasionally necessary in crossing a stream or other obstruction, it is sometimes desirable to make calculations to get approximately the difference between the sag during the winter and the summer months.

For example, in a line crossing a stream with a distance of 300 feet between supports, the sag was 5 feet at temperature of 25° F. What will be the sag at 95° F.?

The length of wire in the 300-foot span at a sag of 5 feet is $L' = 300 + \frac{8 \times 5 \times 5}{3 \times 300} = 300.222$ feet.

At a temperature of 95° F. the rise in temperature is $t =$ 70 degrees, and the length of wire becomes $L' = 300.222$ $(1 + .000096 \times 70) = 302.239$ feet.

The increase in length is 2.017 feet and the sag, assuming no change in the position of supports, would be

$$S = \sqrt{\frac{3 \times 300\,(302.239 - 300)}{8}} = 15.8 \text{ feet.}$$

Thus the sag would be about 10 feet greater on this span in hot weather than during the winter months if there were no elasticity in the supports. In practice, however, the difference would not be over 6 or 7 feet.

Clearance from Trees. — Where primary lines must be carried through trees, care must be taken to provide clearance from limbs as fully as possible. If the necessary permission can be gotten for judicious trimming it should be done. When the trees are very large it is usually preferable to carry the wires through the larger limbs below the main body of leaves. In this case insulators may be attached to the limbs or an abrasion molding to the wires to prevent wearing of the wire and burning of the limbs. Where trimming is not permissible to a sufficient extent to be effective, it is desirable to use tree wire having about $\frac{3}{32}$-inch rubber insulation covered with a layer of steel tape.

Arrangement of Wires. — The position of wires on the cross arms should be assigned according to a systematic plan. Circuits should be kept on the same side of the pole and in the same pin spaces throughout their course, to facilitate location of trouble and to eliminate the possibility of accidents to workmen or property due to misunderstandings. In general, through lines and the highest voltages should be carried on the upper arms. Distributing mains and arc circuits supplying lamps in the vicinity should be carried near the bottom of the line. Secondaries should be carried on the lowest arm to facilitate service work.

The lowest voltages should be carried on the pole pins. Where side arms are used the primary wires should be carried at the outer end of the arm. The wires of a given circuit should be carried on adjacent pins and the neutral of low-tension or secondary wires should be carried in the middle.

On four-wire three-phase lines the neutral should be carried at one side of the phase wires and, except on side arms, on one of the pole pins. With side arms it should be carried on the side of the circuit nearest the pole. In carrying connections across the pole for transformers or services, one side of the pole should be left free for climbing.

Joint Occupancy. — The use of a joint line of poles is preferable to separate lines on thoroughfares where there are many service drops. With lines on opposite sides of the street, the service drops of the lighting company must pass under or through the lines of the signaling company on the other side and vice versa. This introduces many dangerous situations which are eliminated when all drops are taken from one set of poles.

It is usually very undesirable to erect a separate line on the same side of the street with an existing line.

With alley lines the use of joint poles is the safest method unless the lighting line is carried high enough to permit all service wires to be carried above the signaling line. This involves extra expense and is objectionable on that account.

Where poles are occupied jointly by electric light and telephone or telegraph companies, the lighting wires should always occupy the upper part of the pole, as the signaling wires are more likely to break than the lighting lines.

A clearance of about 4 feet should be maintained between the lower lighting wires and the telephone wires. This may be reduced to $3\frac{1}{2}$ feet between the bottom of a transformer and the upper signaling wires. These clearances are necessary for the safety of linemen who may be working on either set of wires.

Transformer Installation. — Transformers are commonly supported on cross arms by iron hangers furnished by the

manufacturers. A typical installation of a small unit is shown in Fig. 129. This class of construction is suitable for transformers of capacities up to 5 kw.

With single units of $7\frac{1}{2}$ to 15 kw. it is usual to use double arm construction for the arms on which the transformer

Fig. 129. Installation of Small Transformer.

hanger irons are carried. Units of 20 to 50 kw. are usually supported on a special 4 by 5 in. arm as shown in Fig. 130, or by some form of bracketed platform placed below the transformer in such a way as to share a portion of the weight. Single units should always be hung in the middle of the cross arm and not at one side. Units of over 50 kw. are supported on a platform almost universally.

Where two or three transformers are mounted on the same pole, they must be so disposed as to give access to primary cut-outs with as little risk as possible to linemen, and this is usually best accomplished by hanging the transformers on one

side of the pole with the cut-outs, and the lightning arresters, if any, on the back side of the double arm, as shown in Fig. 131. With the larger sizes, extra heavy bracing is desirable to take a part of the strain on the arms which support the weight.

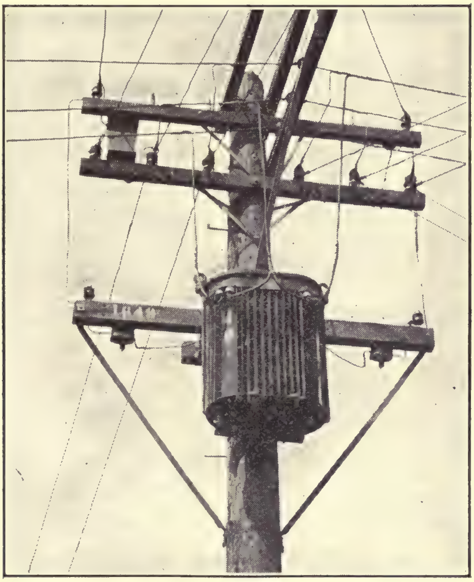


Fig. 130.

It is not usual to support more than about three 30-kw. transformers from a single pole. Two or more poles with a platform between is the preferable method of supporting the larger installations.

Such an installation, consisting of 75 kw. units, is illustrated in Fig. 132. The poles are reinforced at the butt by concrete to increase the stability against side strains. The weight is carried by two 3 by 10 in. timbers bolted to the poles, on which the platform is laid. The primary cut-outs are all accessible from one side of the structure.

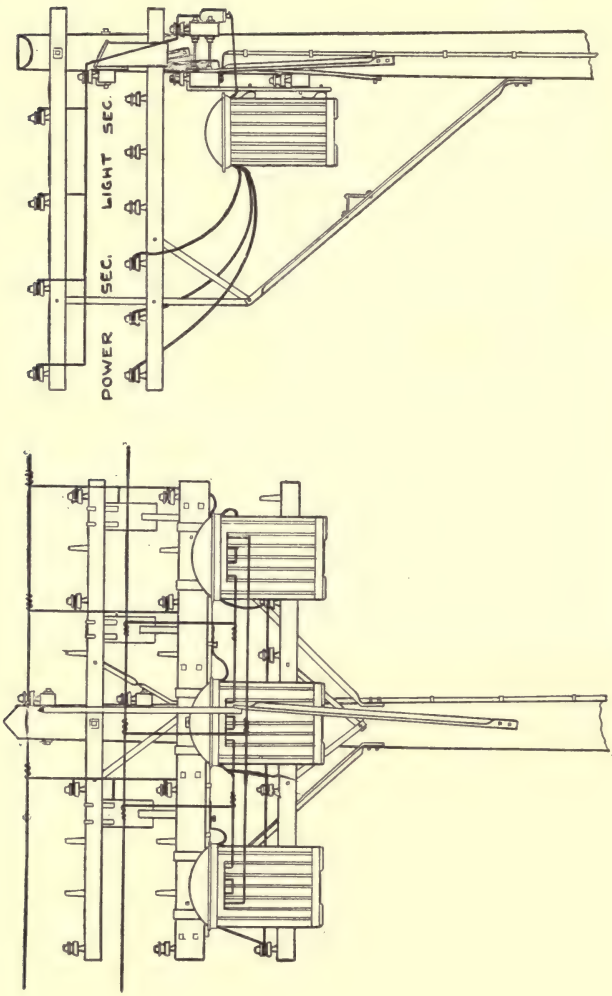


Fig. 131. Three-phase Transformer Installation.

In large three-phase power installations, it is often desirable to be able to resume service with a minimum delay when one unit of a transformer installation fails. This is readily accomplished by providing suitable disconnectives in the

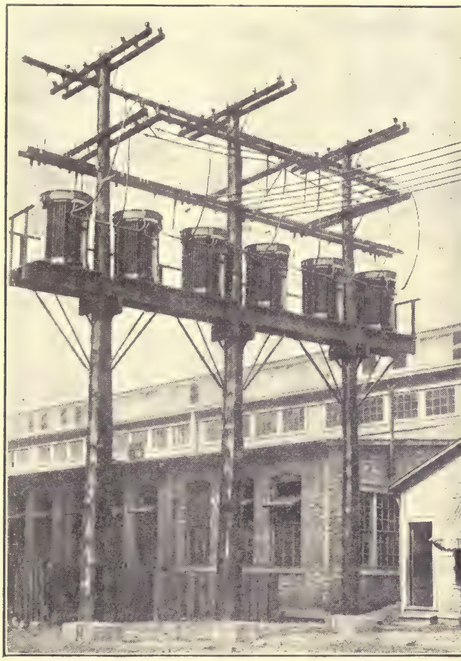


Fig. 132. Transformers on Platform.

secondary leads by which any defective unit can be quickly cut out. The primary may be disconnected at the fuse if there be such. If not, a disconnective single conductor porcelain pothead is found useful for the purpose.

Secondary Grounds. — To protect life and property in case a primary wire becomes crossed with a secondary at any point, it is very important that the secondary be

grounded. This should be done by connecting to water pipes in customers' premises wherever these are accessible. The connection should be made on the line side of the service switch so that it will not be disconnected at any time. Where the ground must be made outside the customer's premises, the most practicable method is to drive a galvanized iron pipe into the ground about eight feet, at the base of a pole near the

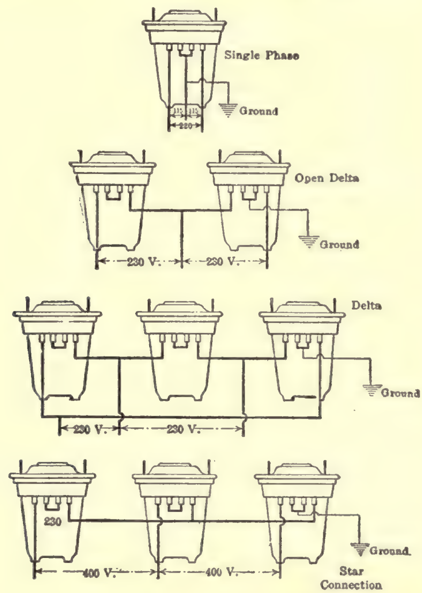


Fig. 133. Secondary Grounding Points.

transformer. If there are more than three spans of secondary main one ground should be installed for every 300 feet of secondary line.

The points to be grounded in various kinds of secondary mains are indicated in Fig. 133.

On a 220-volt single-phase power secondary the neutral point of the transformer winding should be grounded. With a two-phase four-wire power secondary, the mid point of each

transformer winding should be grounded unless the motor windings served are interconnected so as to prevent it. In that event the neutral of one transformer should be grounded. The same procedure should be followed with a three-wire two-phase secondary.

With a star-connected 200-volt or 400-volt three-phase secondary the neutral point of the system should be grounded, giving 115 or 230 volts to ground respectively from each phase wire.

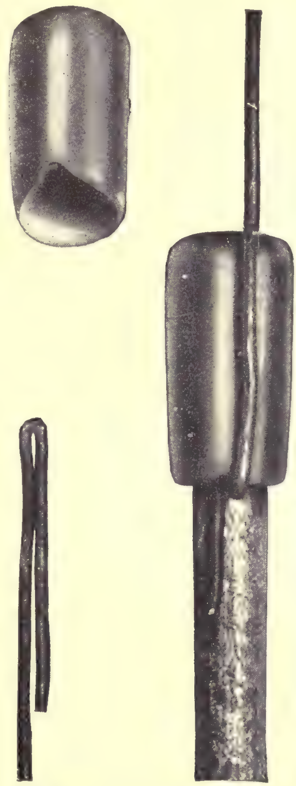


Fig. 134. Ground Wire Connector.

With a delta-connected 220-volt system the ground connection should be made to the mid point of the winding of one transformer. This gives 110 volts to ground from each of the phase wires next to the ground wire and about 200 volts from the other phase to ground. There is some doubt as to the advisability of grounding a secondary when the difference of potential between any wire and ground will be higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal under certain circumstances.

When connection is made to ground through a water pipe the wire should be attached by means of a copper clamp or other connection which may be securely attached to the pipe and wire.

When the connection is made to a pipe at the pole, the ground wire of No. 4 or No. 6 wire is preferably brought down

the pole in a half-round wooden moulding, to protect the linemen and the public from accidental contact. The ground wire may be soldered to the pipe about a foot above the ground, or may be attached by means of a pipe cap as shown in Fig. 103. This cap may be used to drive the ground pipe and at the same time produce a driven contact between wire and pipe. The pipe is usually driven down near to the ground line with this cap in order to minimize the amount of exposed surface.

Service Connections. — Service drops should be tapped near the secondary line insulators and may be supported by them when they can be carried at such an angle from the pole that they will clear properly. Where they leave the pole at approximately right angles they may be supported from iron brackets or from insulators on a buck arm provided for the purpose. If there are several services taken from the same pole the use of a buck arm is the best method, as services can be taken to both sides of the thoroughfare in any desired number from one buck arm.

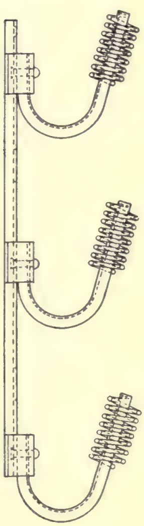


Fig. 135.

Where separate power and light services are maintained, the use of a six-pin buck arm provides facilities for both classes of service. The attachment of service wires to buildings is one of the most troublesome details of distribution work owing to the varying character of buildings, lengths of drops and angle of approach. With frame buildings wooden brackets and spikes are used to some extent for wires up to No. 2 and spans up to 60 or 75 feet. With brick or stone buildings, however, this construction is not reliable. Where three-wire service is required, the necessity of drilling bolt holes for each wire and the necessity for reliable construction

have led to the development of various forms of iron brackets which are supported by expansion bolts when attached to brick or stone buildings.

The wrought iron type of bracket, one form of which is shown in Fig. 135, is supported by two bolts and is made also for support in a horizontal position. This bracket is used for sizes of wire up to No. 4 B. & S. For services of No. 2 to 4–0, a more rugged malleable iron bracket is required. A vertically arranged bracket using standard wooden pins is shown in Fig. 136. In other forms the pins are of iron and integral with the bracket.

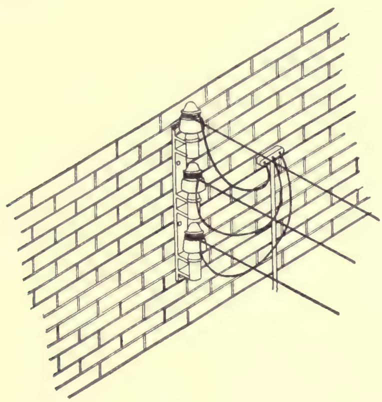


Fig. 136.

Where the appearance of service wires is a material consideration, as in cases where lines are on private property in fine residence districts, the use of a multiple conductor cable for the service drop is desirable. This is also done in some cases where lines are on retail business streets. This usually consists of rubber insulated conductors grouped under an enclosing braid of weatherproofing. Weatherproof insulation is used on the neutral of three-wire service drops. In a few cities weatherproof wire has been used on all conductors without an enclosing braid. The methods of supporting

such drops are not standardized to any considerable extent because of their limited use. The multiple conductor cable is usually attached to an insulator which is supported by a strain wire attached to the cross arm, or building. The use of multiple conductor rubber insulated cable is more expensive than open wire services with weatherproof insulation and its use is therefore limited to locations where it is of value as improving appearances.

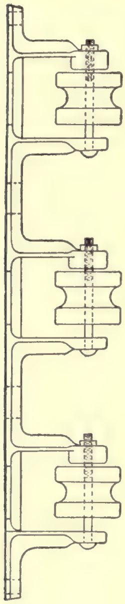


Fig. 137.

The construction of secondary mains on vertical brackets, as shown in Fig. 137, has also been introduced in recent years, as a matter of improving appearances. This construction is well suited to residence districts with detached houses, where not more than two or three drops are taken from any one pole. It is usual to place a vertical bracket on each side of the pole where services are taken off on both sides of the line.

In making a loop on series arc circuits an iron fixture having two pins and so arranged that it can be put in place of a line pin and known as a break arm is used.

Arc lamps for street lighting are supported by a crane from a pole or from a cable strung between two poles and equipped with a pulley by which the lamp can be lowered for trimming purposes. The latter method is usually the less expensive and is used except where the installation of two poles is not practicable or is considered unsightly. In some of the larger cities it is usual to mount lamps on a short bracket without provision for lowering the lamp. In this case the pole is stepped so that the trimmer climbs the pole to trim the lamp.

CHAPTER XI.

UNDERGROUND CONSTRUCTION.

The use of underground construction has been general in the larger cities from the beginning of the electric lighting industry. Considerations of appearance and space prevented the use of overhead lines in the congested parts of the large cities where the early market for electricity was found. The greater first cost was found to have been well justified in the increased security to the service of important consumers to whom an interruption meant financial loss. The development of many of the large city systems proceeded at such a rate that in any event overhead construction would have become physically impracticable within a few years on account of the number and size of the feeders which were required to supply the network.

Edison Tube System. — The underground system devised by Edison was the earliest one to be commercially adopted, and much of this class of equipment is still in service, though other methods are now preferred. The Edison system remained standard for low-tension distribution for about fifteen years and was in many ways an admirable plan of low-tension distribution. It consisted of 20-foot lengths of iron pipe inside of which there were copper rods imbedded in a bituminous compound designed to exclude moisture and to insulate the opposite polarities from each other and the pipe. The rods were wound with a wrapping of jute, to prevent their sagging together, and were further held rigidly apart by separators at the ends. These 20-foot lengths were made

in various sizes of conductor from No. 4 up to 500,000 c.m. for mains and up to 1,000,000 c.m. for feeders.

The Edison Company adopted what became known as the Edison wire gauge for their product. This gauge specified the number of thousands of circular mils in the conductor. The pipe with its conductor was called a tube, and a tube having conductors of 250,000 c.m. was called a 250 tube, or a tube with No. 1 B. & S. conductor was called an 81 tube.

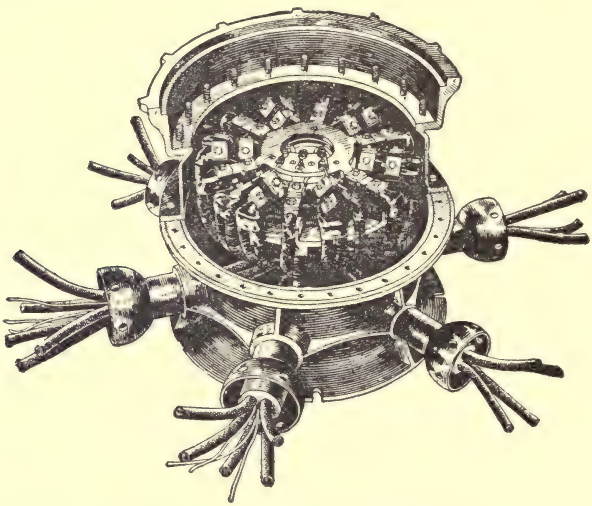


Fig. 138. Edison Tube Junction Box.

Such a gauge became necessary because most of the sizes of tubes were larger than the largest size of any existing standard wire gauge.

Sections of tube which were designed for use as distributing mains were made with three conductors of the same size, while those designed for feeders were made with one conductor about half the area of the others. This small conductor was used as the neutral, as the load on the feeder was nearly balanced and little capacity was required in the neutral.

Feeder tubes were also provided with three small wires which served as pressure wires to indicate the feeder end pressure at the station or substation.

The sections of tube were laid in the ground without other protection than would be given water or gas pipes. The copper rods were joined by means of soldered lugs with stranded flexible connectors. These connections were enclosed in cast-iron couplings, which were filled with hot compound after being bolted in place on the tubes. At intersections the tubes were interconnected through junction boxes, which carried the necessary fuse clips and nuts by which a main was automatically disconnected in case of breakdown, or could be opened by repair men for testing purposes. These boxes were made so that 4, 6, 8 or 10 tubes could be brought together in one box, as was necessary at the intersection of two streets where a feeder was tied in, and where there were lines going each way on both sides of the street.

Tube lines were carried along each side of the street near the curb to facilitate the introduction of services into consumers' premises. A single line was run where the consumers were scattered and where the alleys were used. Service connections were made by a T connection applied at any joint in the line. The service tube was carried through the building wall into the sidewalk area or into the basement of the building. Where the buildings were not built out to the property line, the service was extended underground across the consumers' premises or brought up on a pole at the lot line and carried thence overhead to the building. The expense of the line across the private property was usually borne by the consumer, and the decision as to the method of installation commonly rested with him in such cases.

The Edison tube system was the standard method of distributing low-tension current underground until about the

year 1897, when cables drawn into ducts began to be employed for the heavy feeders. This change was made on account of

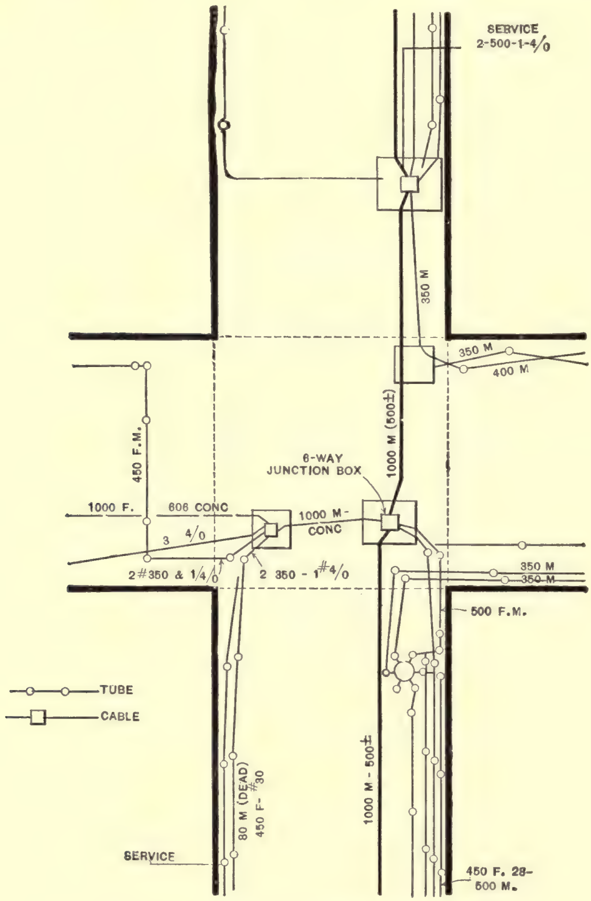


Fig. 139. Edison Tube and Cable System.

the inability of the tube feeders to carry overloads without melting the compound in the joints and causing burn-outs. With cable it was found that the copper could be run with

heavier loads, and therefore more economically from an investment standpoint.

Furthermore the necessity of opening street pavements in each case where repairs were made involved considerable expense, as several openings were usually made before the trouble could be definitely located.

The feeder system and the heavier distributing mains were therefore gradually worked over to a " draw-in " cable system as rapidly as reinforcement was needed from year to year. The systems as they exist, therefore, embody a combination of cable and tube work such as is shown in Fig. 139, which illustrates the feeders and mains at an important street intersection in Chicago. The tube system is not being generally extended at the present time, but on side streets where no through lines are required and the load is not heavy, the simplicity of the tube system is retained by laying a single 3-inch iron or bituminized fiber duct into which lead-covered cables are drawn.

Service connections are made in a manner similar to the tube services, the joints being enclosed in a T coupling box of iron. The cost of such construction is about the same as that of Edison tube work, and it is therefore supplanting Edison tube work in cases where such construction is desirable.

Early Conduit Systems. — The early alternating and series arc systems which were installed in situations requiring underground constructions were unable to use a system similar to the Edison tubes because of the higher voltages employed. The engineers were therefore compelled to seek other means of installing their conductors. A variety of materials was tried, but the method was that of a draw-in conduit system with manholes for handling the cables in nearly every case. One of the earliest was the Dorset system, which consisted of sections

of multiple duct made up of an asphaltic concrete joined together by pouring hot compound around the joints. These joints failed to remain in alignment and the asphalt ducts became distorted, so that the work of installing cable became difficult if not impossible.

Creosoted wooden pump log was tried because of its ease of jointing and low cost. It was very satisfactory for some classes of work, but was too short-lived for important lines, and took fire too easily in case of failure of cable, the creosote with which it was impregnated being inflammable.

Paper tubes impregnated with bituminous compound were tried in some cases. These were laid in asphalt and the conductors were drawn in without insulation. It was expected that the insulating qualities of the paper tubes would be sufficient to be practical. The presence of moisture, however, could not be wholly prevented and the tubes therefore absorbed water at the manholes and this caused the conductors to become short-circuited and burn out. It was practically impossible to make repairs, and the system failed.

In another plan the bare conductors were drawn through 1-inch holes in a wooden tube which was surrounded by an iron pipe and immersed in oil. The manholes were also kept partly filled with oil to cover the ducts, but as moisture could not be excluded and the difficulty of adding to or repairing high-tension conductors was great, this system failed.

Other systems were developed in which the ducts were intended to provide insulation for the conductors, but experience proved that it was not at all practical to maintain such a system, and all such attempts were abandoned.

The efforts of engineers were then directed to systems in which the construction was more nearly fireproof, of greater durability, and yet economical to construct and maintain.

This naturally led to the development of methods in which the insulation was applied to the conductor and the conduit

was of some fireproof material which would be durable underground.

Among the earlier forms of duct of this sort was one which consisted of sheet-iron tubes lined with cement. It was made in 4-foot lengths, with ferrules at the ends to preserve the alignment, and when properly laid obviated many of the difficulties experienced with the earlier forms of duct. A considerable amount of it was installed in some of the larger cities. Where it has been subjected to cable burn-outs with large power behind, it has been found, however, that the cement does not hold up under the heat of an arc, and that the metal sheathing is apt to assist in the spread of the short circuit. The use of this form of conduit has, therefore, not been continued in recent years.

While these various forms of duct were being tried out, other engineers were introducing ducts of terra cotta and clay tile. These materials being fireproof and of indefinitely long life, it only remained to work out the best form of duct and a suitable way of laying it. Multiple and single duct was tried and the alignment and security from outside interference were gotten by protecting the ducts by concrete or creosoted plank. The supply of clay is abundant and the expense therefore somewhat less than with other ducts. This class of construction is the most generally used where a draw-in system is employed.

A substitute for clay tile was developed in later years consisting of a concrete duct, known as "stone conduit." This is made by pouring a suitable mixture of stone, sand and cement into molds about four feet long and three and one-half inches inside diameter, where they are left until sufficiently set to bear handling. They are seasoned from two to three months and then fitted with sheet iron ferrules which are centered carefully with the inside of the duct, so that alignment will be assured when laid. The 4-foot lengths are laid with joints

staggered in a surrounding jacket of concrete, thus making a solid line of concrete which is very durable. This type of duct is somewhat cheaper than tile duct at the factory but the breakage in shipment is greater and construction gangs must be given some training in handling to prevent excessive breakage after delivery. This, however, is not difficult and large quantities of stone conduit have been laid in and near Chicago.

In the effort to get an insulating conduit, the use of paper or fibrous tubes impregnated with moisture repellent compounds was tried. The earlier forms of this type of duct were not strong enough mechanically to prevent collapse under continuous exposure to moisture. In later years, however, processes of manufacture were developed which produced a very dense form of fiber duct, having ample mechanical strength when surrounded by concrete, and not readily inflammable. This type of duct is made in lengths of about five feet, is easily handled because of its light weight, and when laid with concrete between adjacent ducts makes a quite durable structure. It has advantages for cross country lines where transportation and breakage of tile duct is expensive, for telephone and similar systems where no fire hazard is present, and has been used for light and power distribution to considerable extent.

Laying out a Conduit Line. — In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the important considerations.

The *number of ducts* must be fixed by the requirements of the route to be followed. There must be sufficient to care for the local distribution, for distributing feeders, for transmission lines and for future requirements. The distributing mains for a low-tension system usually fill one duct, but with alternating mains and underground secondaries two ducts

must be reserved in many parts of the system. The feeder and transmission line requirements are fixed by the proximity to stations. The reservation of duct space for future requirements is very important if the system is a growing one, as the expense of adding a few ducts at a later date is much larger than if they are laid when the trench is open. It is therefore desirable to lay sufficient ducts in advance to care for probable requirements for at least five years ahead. It is not advisable to lay less than four ducts in a line except on side streets where there is no probability that the line will ever become part of a through line. In such cases two duct lines are installed where a single pipe with a low-tension main will not meet the requirements.

The maximum number of ducts which it is advisable to put into a line is governed somewhat by the local conditions but chiefly by considerations of safety to the cable equipment.

If a large number of ducts is placed in one line, the amount of cable exposed to injury in case of a manhole fire is great, and the resulting interruption for service may be very serious. In the vicinity of stations and substations where large numbers of ducts must be provided, it is therefore good practice to limit duct lines to about 24 ducts as a maximum. The cost per duct foot for lines of 30 to 50 ducts is not sufficiently below the cost of a 20 or 24 duct line to make it especially advantageous to build larger duct lines from an investment standpoint.

In arranging the duct formation it is desirable to place the ducts so that the cross-section will be approximately square, since this requires a minimum of concrete in the outer casing. Thus a four-duct line should be 2 ducts high and 2 ducts wide. Six ducts may be 2 by 3 or 3 by 2; 8 ducts are sometimes laid 2 by 4, but it is practically no more expensive to add a duct and make it 3 by 3.

With 12, 16, 20 or 24 duct lines it is preferable not to ex-

ceed 4 ducts wide in order to avoid undesirable conditions in manholes. With 20 ducts arranged as in Fig. 140, a double row of cables may be trained around each side of the manhole, making all cables accessible for subsequent changes in connections or for repairs. With more than four ducts in a horizontal row, the cables become less accessible or the training is less orderly.

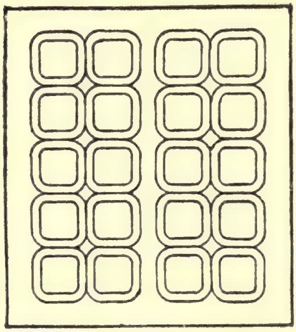


Fig. 140. Divided Arrangement of Ducts.

In large systems where the energy available in case of a cable burn-out is sufficient to do considerable damage to the conduit system, it is desirable to separate the two middle vertical rows of lines having 12 or more ducts by filling the space with about three inches of concrete. This limits the damage to cables to one-half of the line, if the burn-out occurs outside of a manhole. Trouble in manholes may be segregated in a similar manner by a divided manhole as shown in Fig. 141.

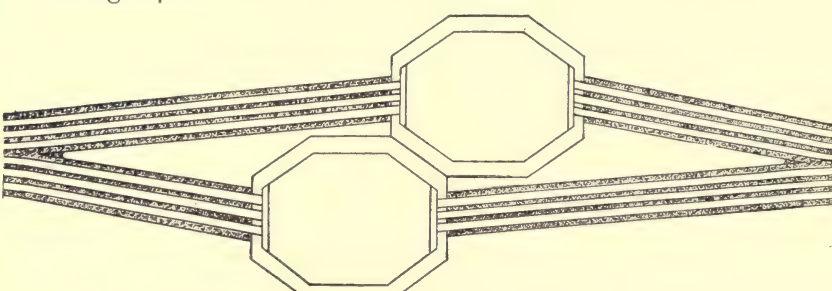


Fig. 141. Divided Manhole.

This construction is advisable in manholes near generating stations, where there are many cables and the severity of a burn-out is great because of the proximity to the source of supply. The arrangement shown in Fig. 142 provides a ready

means of bringing cables from a number of outlets to a number of conduit lines running in two directions without having a tangle of cables in the manholes. By this plan, a cable can be taken from any outlet to any conduit line, without cross-

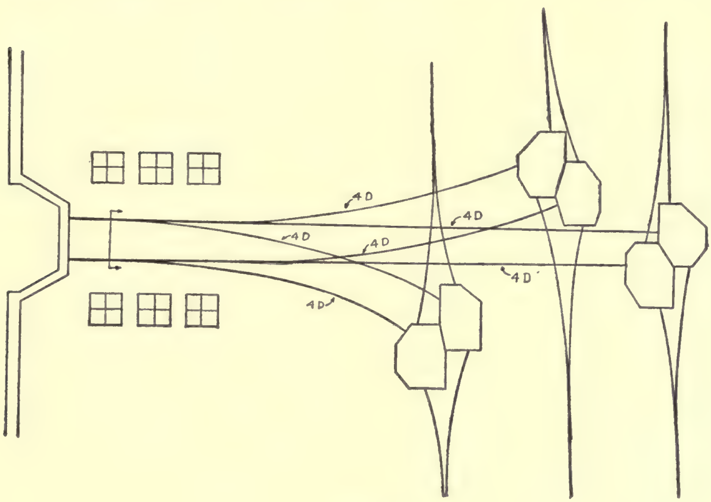


Fig. 142.

overs, and cutovers may be made subsequently without disturbing the general scheme or introducing complications.

Location of Manholes. — The use of a draw-in system involves the construction of vaults called manholes at all points where the cable must be jointed and where lines turn or intersect.

Where long runs occur without intersecting other lines, manholes must be provided with sufficient frequency to permit the drawing in of cable without damage to the cable insulation. This usually requires that they be not over 500 feet apart, and with large cables which nearly fill the duct 400 feet is a safer limit.

The location of manholes on a length of line which is not intersected by other duct lines at each block should be made as far as possible with a view to their being used as intersection points later. That is, they should be located so that any conduit line built on an intersecting street later may be connected with existing manholes. It is impossible to predict with certainty which side of an intersecting street will be used, but the location of manholes at street and alley intersections will minimize the necessity for duplication. Where distribution by overhead lines in alleys with underground lines on the street is used, manholes should be put opposite alley intersections where it is practicable to do so.

The number of manholes required in blocks where numerous underground service connections are required is dependent somewhat upon local conditions, but must usually be sufficient to permit service pipes to be brought into sub-sidewalk areas or basements at intervals as required. In the denser portions of the system this results in the location of small manholes at intervals of 75 to 125 feet, while in other parts they may be 150 to 200 feet or more apart. In distribution by means of underground transformers and a secondary network, it is necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

Design of Manholes. — The size and shape of manholes are varied to suit the requirements in different situations. Manholes located in a straightaway line should be so designed that the cables may be trained around the sides with a minimum of waste cable and yet with sufficient space to enable a jointer to work efficiently. Such a manhole is illustrated in Fig. 143. The oval shape permits of easy training of cable, and the width of four feet is ample to allow the jointer room to work with any number of ducts up to nine. Where the line intersects another duct line, a design must be used which

gives room for cables going both ways and which will afford room for work as well. At such points a square design is preferable, as shown in Fig. 144. The smallest size ordinarily used for such points is five feet square. Where many cables

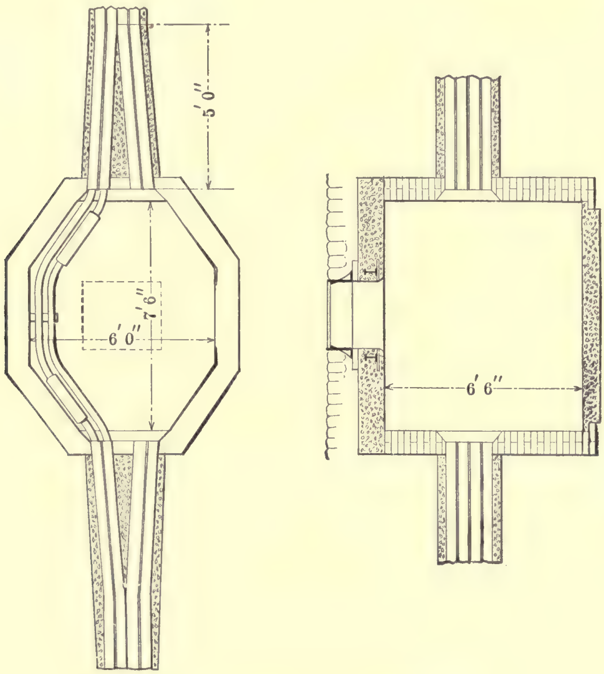


Fig. 143. Manhole for Through Line.

are involved or where room is required for low-tension junction boxes or transformers, dimensions of 8 feet by 8 feet or larger are often necessary. Where it is likely that many splices will be made or other work of construction or maintenance done frequently, it will be found to be most economical in the long run to provide manholes of ample size for convenient working space. The money saved by reducing the dimensions of

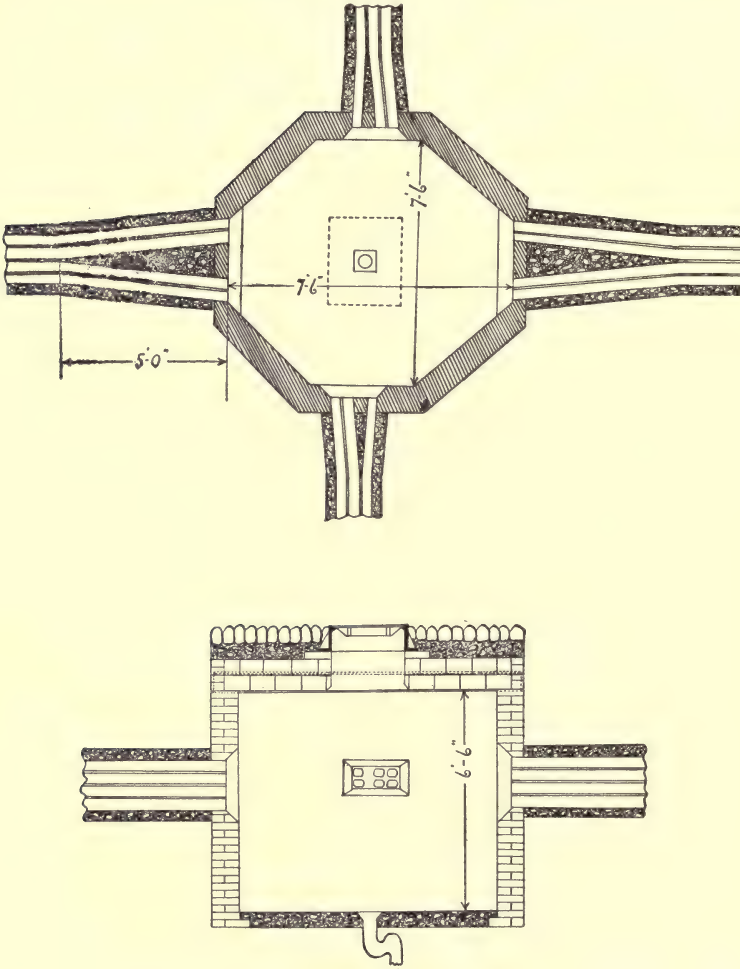


Fig. 144. Manhole for Intersections.

a manhole one foot may be spent several times over in extra cost of work done on cables in the manhole in later years.

In a growing system it is a matter of judgment as to what the requirements in the way of space are likely to be. The

space required for cables is fixed by the number of ducts coming into the manhole, and this must be sufficient to allow of training these cables safely and with a reasonable degree of accessibility for repairs or changes. The probable installation of junction boxes or transformers must be taken into account also. In practice it is usual to provide manholes 5 feet by 5 feet at junctions where there are eight ducts, that is, where two 4-duct lines cross, 6 feet by 6 feet where there are 12 to 18 ducts, 7 feet by 7 feet where there are 20 or more, and larger as the needs of the case may require.

The size and shape of manholes in congested districts are often governed by local obstructions such as gas or water mains and services or the conduit lines of other public service companies. Manholes must frequently be built so as to include a gas or water main, and the size must be increased to get the necessary space.

The depth of manholes must be sufficient to give head room and yet should preferably not be so great as to carry the floor of the manhole below the sewer level. Small distribution manholes which are used only for service connections may be more shallow than larger holes where work is done frequently. Service manholes may be 5 feet inside, while junction manholes should be 6 or 7 feet from roof to floor. In some cases a shallow form of manhole known as a handhole is used for distribution laterals. These are made about 3 by 4 and 3 feet deep. They are placed above the conduit line, so that only the top row of ducts enters the hand hole. The distributing mains are thus accessible for service taps and the through lines in the lower ducts are not in the way. Service laterals are usually laid just under the paving, so that they enter the handhole at a convenient level. Handholes should have covers large enough to afford access to the distributing main.

Service Connections. — The arrangement of service laterals or subsidiary connections from the main duct line to consumers' premises is a matter of much importance, as it forms a large part of the underground investment in congested districts. Local conditions often fix the character of the design, so that no universal method can be laid down as better than all others. In some cities a separate service lateral is not required for each building into which service is to be introduced and the laterals may be placed at intervals of 75 to 100 feet or more, the intermediate buildings being connected by means of interior wiring through sub-sidewalk areas or building basements. This method is much less expensive than that required in cities where each building must have its own service connection, as it requires fewer distributing handholes or manholes and a much less mileage of lateral pipe and service cable.

Where service laterals can be spaced 100 feet or more apart a single duct line is sufficient to care for the service on both sides of the street. Lateral connections are run to each curb or building line from the service manholes. With a street more than 100 feet wide, it may be more convenient to use two duct lines to save the long laterals. In very congested districts it is advisable in this class of construction to put in double laterals each way to facilitate repairs or changes in the cable work or to give emergency service to important consumers.

Where separate service is required for each building, this plan may result in the installation of manholes or handholes at intervals of 50 feet as in Fig. 145, where buildings are on 25-foot lots and service is required n nearly every building. In such cases it is less expensive in the long run to establish service handholes at intervals of about 100 feet on each side of the street. The arrangement shown in Fig. 146 is worked out for a street 66 feet wide, with 34 feet between curb lines.

This arrangement requires less lateral cable and pipe and is the most feasible arrangement in streets where there are car tracks under which laterals must be carried. The advantage

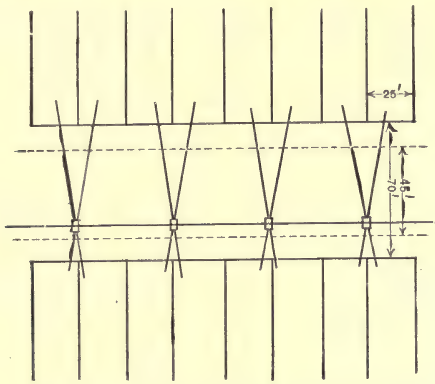


Fig. 145. Service Handholes and Laterals.

of the construction shown in Fig. 146 increases with the width of the street. It is also an advantageous plan where there is a parkway in which the laterals can be laid, no paving being disturbed except at the street intersections.

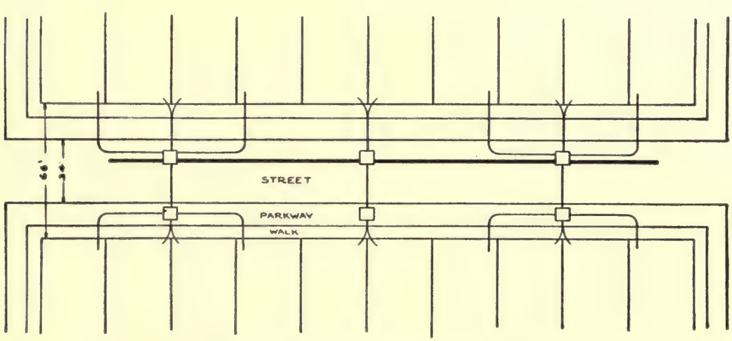


Fig. 146. Double Handholes for Service Connections.

Location of Duct Lines. — In the location of a duct line the presence of other piping systems, duct systems, sewer manholes and the like must be taken into account. It is desirable

to select the side of the street which is least obstructed by such obstacles. The municipal records should be consulted to get the location of the water piping and sewer systems, if such records are available. Other duct systems may be located by the manhole covers which appear on the surface.

In crowded streets and where records are not available, time is saved by excavating a test trench across the street at several points for the purpose of locating the piping and other systems which cannot be identified from the surface.

Specification for Tile Duct. — Tile duct is made of clay which is worked up in a pug mill to the proper consistency, passed through a press from which it emerges in the desired shape, carefully dried and burned in a kiln until it is thoroughly vitrified. It is then given a salt glaze and allowed to cool slowly.

The quality of the duct is affected by many of the processes very materially and it is therefore important that it be purchased under careful specifications. Some of the more important points follow:

The clay should be of such composition that it will be free from gravel and will work up into a solid homogeneous mass. 60 per cent fire clay and 34 per cent shale make a very desirable combination.

The duct when molded and dried should be burned through but not scorched or fused. The glaze should thoroughly cover the inside of the ducts so that they will present a smooth surface to the cable.

Single duct should not have a bend of over $\frac{1}{8}$ inch from a straight line and multiple duct should not have a more than $\frac{3}{16}$ inch bend. Twisted or distorted pieces should be rejected, as they cannot be lined up and may interfere with rodding the duct.

No duct having salt blisters or drips which project more than $\frac{1}{8}$ inch inside or $\frac{1}{4}$ inch outside should be used.

Air- or fire-checked pieces should not be accepted.

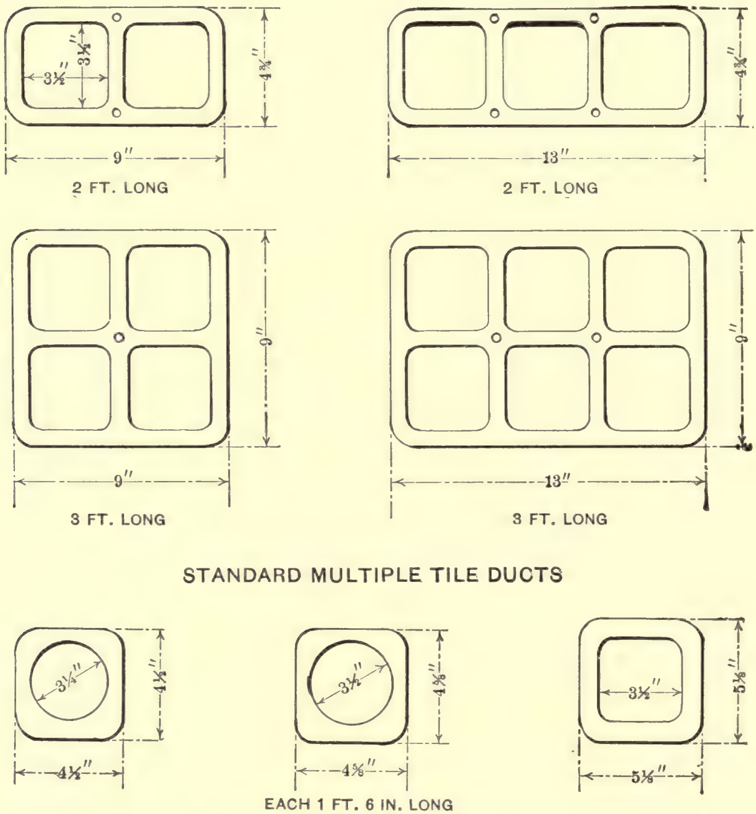
The test for straightness should be made by passing through the duct a mandrel of the length of the piece and $\frac{1}{8}$ inch smaller than the inside of the duct. If the mandrel will not pass, the duct is too crooked to be safely installed.

If the tile is properly vitrified it will give a clear ringing sound when struck with a piece of tool steel $\frac{1}{2}$ inch by $\frac{3}{4}$ inch. If not, it gives a dead sound which indicates softness and porosity, which will result in too high a rate of breakage in handling if accepted.

Forms of Duct. — Tile conduit is made in single- or multiple-duct pieces. Single-duct pieces are usually about 18 inches in length, while multiple duct may be made 36 inches long. The greater length is desirable in reducing the labor of laying, but is not practicable in single duct on account of breakage. The dimensions of ducts in general use are shown in Fig. 147. The duct having a square hole is preferable, as cable may be pulled into it more easily. Multiple duct is somewhat cheaper than an equal number of single ducts, and it requires less labor to lay it. In a large system, with the danger of injury when an arc is maintained in the duct, it is considered preferable to use single duct to secure the advantage of having two thicknesses of tile between adjacent ducts. This better protects the cables in adjacent ducts from injury in case of burn-outs. The single duct also has the further advantage that the joints may be staggered, thus making it more difficult for the heat of a burn-out to damage cables in adjoining ducts.

Installation of Conduit Lines. — In laying a line of ducts the grades must be carefully established so that the duct line

will tend to drain toward the manholes. If pockets are formed, the standing water is likely to freeze in winter weather and injure the insulation of the cables and break the tile.



STANDARD SINGLE TILE DUCTS

Fig. 147. Forms of Tile Duct.

It is important that manholes where work must be done frequently or where transformers or junction boxes are installed be connected to the sewer. The accumulation of

water in such a manhole may start trouble or may seriously delay repair work which is urgent.

The conduit line must be protected, when laid in public thoroughfares, from future excavators. It should also be made secure against the possibility of getting out of alignment and thus injuring the cable or making it impossible to pull cable in or out. In view of these considerations it is usual to surround important lines with concrete on all sides to a thickness of three inches. This makes an envelope thick enough to support short sections around which excavations may be made later and also protects the tile from the laborer's pick. The concrete when set acts as a watershed to a large extent and minimizes the entrance of leaking gas into the conduit system.

The use of concrete is general where the service is important and the frequency of subsequent excavations is a considerable factor.

With lines built in parks or on roadsides it is sometimes sufficient to lay the ducts on two-inch creosoted plank with a similar plank over the top of the ducts. Such construction is less expensive in first cost, and if not disturbed is quite durable.

Where the space for installation of conduit is limited as in crossing under street railway tracks, water pipes, etc., the change in grade may be minimized by making a short section of line with a flat formation, one or two layers high. In such cases it is often simpler to use wrought iron pipe without concrete, for the section of ducts where the crossing occurs. A manhole is built each side of the obstruction.

The construction of manholes is dependent largely upon the particular use to which they are to be put and must often be modified to suit conditions which vary widely.

Where excavations can be made without interference with other piping or duct systems, manholes may be economically

constructed of concrete according to a standard design for which forms may be used. When any obstruction is encountered the form is not practical and walls must be built up of brick. In most cases the floor may be made of concrete without difficulty, as no forms are needed.

The brick should be of the quality known as sewer brick and should be laid up with a good cement mortar, an 8-inch wall being ample for the requirements in most cases. The roof must have sufficient strength to support the heaviest street traffic, and its design therefore varies with the size and shape of the manhole. In general the necessary strength is secured by the use of steel beams or angles as a framework. Worn rails are sometimes a cheap form in which to purchase steel for such purposes. The framework is filled in with brick or concrete arches. Manhole covers and frames are made of cast iron of rugged design, the top surface of the cover being made rough to prevent accidents to teams or pedestrians. In heavy lines it is very desirable to provide openings in the covers for purposes of ventilation. The amount of heat liberated in a heavy line of low-tension cables is very appreciable, and ventilation must be provided to keep the temperature as low as possible. The ventilated manhole is also much less likely to accumulate gas in sufficient quantity to cause an explosion or to interfere with work. Serious explosions have occurred in manholes which were not ventilated.

Cost of Conduit Construction. — The cost of underground work has been discussed by several writers, notably W. P. Hancock, who presented a paper which appears in the 1904 Proceedings of the National Electric Light Association, and Louis A. Ferguson, whose paper was read before the International Electrical Congress at St. Louis in 1904 and appears in the proceedings of that body.

The figures given by Mr. Hancock represent experience in

the city of Boston primarily, while those of Mr. Ferguson were taken from work done in the city of Chicago.

The figures agree quite closely in the final results as to total cost, though arrived at differently, and they may therefore be taken as applicable to those portions of any city where a high grade of construction is justified.

These costs are computed on the basis of labor at rates per hour which are now (1916) rather low for most cities. They may be readily corrected for any other scale of wages as the case may require, by applying the correct rates to the individual items.

The figures in Table IV are those of Hancock, showing the cost of conduit without manholes for a 15-duct line laid up with single tile. Table V shows the elements of cost for a 5 by 5 by 7 feet deep manhole. The walls are of brick and the floor and roof of concrete. Table VI shows the cost of duct lines of various sizes laid up from single tile without manholes, as given by Ferguson.

The costs of repaving are approximately as follows: Cedar block 60 cents, macadam 50 cents, granite blocks $1.00, asphalt $3.25 per square yard. These costs are higher if it is necessary to open up paving within the period in which the contractor's reserve is still effective, as the opening can be made only with his permission and subject to the terms dictated by him for repaving.

Table VII gives the cost of the more common sizes of manholes, as reported by Ferguson. These figures include sewer connections, concrete roof and floor, with brick walls, but not repaving. The dimensions are given with depth from floor to roof inside the manhole as the last figure in each case.

TABLE IV. — COST OF 15-DUCT LINE.

	Per duct foot.	
Lumber at $15 per M	$.0105	
Concrete at $4.85 per yd	.0231	
Mortar at $3.98 per yd	.0026	
Tile at $.05 per ft	.0502	
Total material		$.0864
Excavation and filling at 15 cts. per hour	.0266	
Placing lumber at 20 cts. per hour	.0004	
Placing concrete at 15 cts. per hour	.0029	
Placing mortar at 25 cts. per hour	.0016	
Laying tile at 50 cts. per hour	.0040	
Hauling away dirt at 50 cts. per hour	.0047	
Total labor		.0402
Inspection, 50 cts. per hour		.0033
Engineering expenses		.0214
Incidentals, 5 per cent		.0116
Per duct ft		$.1629

TABLE V. — COST OF 5×5×7 MANHOLE.

23.7 cu. ft. concrete at $.202	$4.78	
2500 bricks at $9.00	22.50	
1013 lbs. railroad iron at $.0125	12.67	
Manhole frame, 962 lbs. at $.015	14.43	
$1\frac{1}{8}$ yds. mortar at $3.98	4.47	
Sewer trap	5.65	
30 feet sewer pipe at $.30	9.00	
Total		$73.50
Excavation and filling 785 yds. at $.0278	$21.82	
Repaving at $1.44 per sq. yd	11.95	
Removing dirt	4.30	
Laying brick	7.00	
Total labor		49.07
Grand total		$122.57

TABLE VI. — APPROXIMATE COST OF SINGLE-DUCT CONDUIT (IN CENTS) PER DUCT FOOT.

No. of ducts.	Cost of repaving per square yard.						
	No paving.	$0.50	$1.00	$1.50	$2.00	$3.00	$3.50
2	24	29	34	38	43	52	56
4	22	25	27	30	33	38	41
6	20	22	24	26	28	32	34
9	19	21	22	24	25	28	30
12	19	20	21	23	24	26	28
16	18	19	20	21	22	24	25
20	17	18	19	20	21	22	23
24	17	18	18	19	20	21	22
30	16	17	17	18	19	20	21
40	16	17	17	18	18	19	20
50	16	16	17	17	18	19	19

The number of duct feet and manholes of each size having been laid out on a plan, the cost of the conduit line may be estimated from these tables with fair accuracy, the kind of paving and other local conditions being known.

For instance, with a macadam-paved street, what will be the cost of a 4-duct line 1000 feet long with two 5 feet by 5 feet by 6 feet and two 3 feet by 3 feet by 4 feet manholes? From Table VI the cost of a 4-duct line with paving at 50 cents is .25 per duct foot. There being 4000 duct feet the conduit proper will cost $1000. From Table VII the cost of the two 5 feet by 5 feet by 6 feet manholes wil be $123.23 each, or $246.46, while the two 3 feet by 3 feet by 4 feet manholes will cost $46.50 each, or $93. The 5 feet by 5 feet by 6 feet manholes require 10.67 square yards of repaving each, or 21.34 yards, and the two small manholes require 8 yards. The cost of repav'ng 29.34 square yards at 50 cents will therefore be $14.67. The entire cost of the work will therefore be

Conduit	$1000.00
2 large manholes	246.48
2 small manholes	93.00
Repaving	14.67
Total	$1354.15

TABLE VII. — COST OF MANHOLES, EXCLUSIVE OF COST OF REPAVEMENT.

Material.	3'×3'×4'		4'×5'×5'		5'×5'×6'		6'×6'×6'		7'×7'×6'		8'×8'×6'[1]	
	Quan.	Amt.	Quan.	Amt.	Quan.	Amt.	Quan.	Amt.	Quan.	Amt.	Quan.	Amt.
Excavation and removal of dirt at 87½ cts. per cu. yd....	3.70	$3.24	7.77	$6.80	16.30	$14.26	19.00	$16.63	24.00	$21.00	29.63	$25.93
Brickwork — sides at $9.50 per cu. yd....	1.67	15.86	2.92	27.74	4.17	39.62	4.50	42.75	5.17	49.12	5.83	55.39
Concrete — bottom at $7 per cu. yd....	......	......	.37	2.49	.56	3.92	.67	4.69	.91	6.37	1.18	8.26
Concrete — top at $8 per cu. yd....	.56	7.00	.96	7.68	1.35	10.80	1.55	12.40	2.01	16.08	2.50	20.00
Iron in roof at 3 cts. per pound	105 lb.	3.15	129 lb.	3.87	153 lb.	4.59	178 lb.	5.34	215 lb.	6.45	227 lb.	6.81
Sewer connection and permit at $25 each....	......	......	1	25.00	1	25.00	1	25.00	1	25.00	1	25.00
Trap and backwater valve at $6.50 each....	......	......	1	6.50	1	6.50	1	6.50	1	6.50	1	6.50
Sewer grates at 30 cts. each..	......	......	......	.30	......	.30	......	.30	......	.30	......	.30
Frame and cover at $15 each .	1	15.00	1	15.00	1	15.00	1	15.00	1	15.00	1	15.00
Supervision and incidentals...	......	2.25	......	2.25	......	2.25	......	3.25	......	3.25	......	3.25
Totals....		$46.50		$97.63		$123.24		$132.06		$149.07		$166.44
Sq. yds. repaving required....	4.00		8.89		10.67		12.00		13.89		16.00	

[1] Last dimension is depth. Depth of manhole given in the clear inside dimension

The total cost including manholes and repaving is therefore equivalent to 33 cents per duct foot. If the paving had been asphalt at $3.25 per yard the conduit proper would have cost 40 cents per duct foot, or $1600, and the manhole repaving would have been $95.35, making the total cost $2034.83. It is therefore important in selecting routes for through lines to choose those thoroughfares in which the cost of repaving will be a minimum.

CHAPTER XII.

CABLE WORK.

Types of Cable. — Cables used for the underground distribution of electricity consist of a conductor or group of conductors insulated suitably for the voltage at which they are to be operated and enclosed in a lead sheath for protection from moisture. If the cable is to be laid without the protection of a conduit system, it may be further protected from mechanical injury by an armor of steel tape or wire. It is then known as an armored cable. The use of a lead sheath is necessary if the cable is to remain in service permanently as the insulation is impaired if exposed continuously to moisture and the life is materially shortened. Cables having but one conductor are known as single-conductor cables, those having two conductors are known as duplex or twin and those having three conductors as triplex or three-conductor cables.

Duplex and triplex cables are those in which the conductors are spirally arranged in the lead sheath, the voids being filled with jute to make cable of circular cross-section as in Fig. 148. Twin cable is that in which the two conductors are arranged in one plane without twisting or filling in the voids with jute.

Two-conductor and three-conductor cables are also made with a concentric arrangement. After the central core is insulated for the intended voltage, the strands of the next conductor are spirally wound around it and the insulation is applied in the usual manner.

If it is to be a two-conductor concentric cable, the lead

sheath is then applied. If not, another layer of copper and insulation is added, making it a three-conductor cable before the lead is applied.

Where it is necessary to get the maximum cross-section of copper within a given diameter of lead sheath, the copper con-

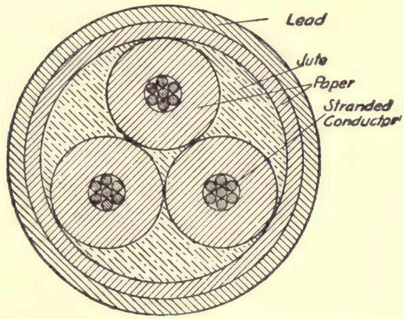


Fig. 148. High-voltage Cable Insulation.

ductors are stranded so as to make a cross-section shaped like a sector of a circle. This permits the use of more copper in a given space as the copper occupies a part of the space which is otherwise filled with jute.

Cables having as many as 10 or 12 conductors of No. 6 or No. 8 A.W.G. have been used to some extent for series lighting circuits, where all the circuits were carried underground through a district without loops.

The use of multiple-conductor cables is generally advantageous because of the saving in the cost of the lead sheath as compared with an equal number of similar single-conductor cables. However, there are certain disadvantages incidental to taps and joints which tend to offset some of the advantages. Practice therefore varies according to the use to which the cable is put.

In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while concentric

and other multiple-conductor cables are used for through lines where taps are not made. Twin cable has been used quite extensively in series arc systems, and in single-phase taps of alternating-current systems. It is difficult to train in manholes, as it does not bend easily in the plane of the conductors, and with paper insulation is susceptible to injury from bending at too small a radius.

Concentric cables are used in preference to duplex where the conductors are over No. 0, as the side-by-side arrangement makes a cable which is very difficult to bend, and in the larger sizes cannot be drawn into a standard duct. The greater facility of jointing makes the use of duplex somewhat preferable in the sizes below No. 0 A.W.G. The concentric arrangement is especially advantageous with low-tension feeders, as it permits the use of a single duct for the outers of an Edison feeder of 750,000 or larger where two ducts would be required if single-conductor cables were used. This is of importance where feeders are numerous and duct space limited, as is often the case in the larger cities.

Low-tension distributing mains which have three conductors of the same size should preferably be of single-conductor cable, in order to facilitate the work of making service taps. This work must be done with the lines alive, and is much more easily accomplished when one polarity may be dealt with at a time. The same is true of service cables which are terminated in damp basements or sidewalk areas where good insulation is maintained with difficulty and where the separation of polarities is very desirable.

Two-phase and three-phase feeders from which few taps are taken are preferably of three- or four-conductor cables, owing to the lower cost of a single lead sheathing as compared with the same number of single-conductor cables. The use of single-conductor on the primary mains is preferable from the standpoint of the expense of jointing and separation of po-

larities. It is also desirable to use single-conductor cables at points where multiple-conductor feeders are connected to an overhead section, as this makes a safer installation to handle on a pole top.

Secondary cables carrying loads of 200 amperes and upward are subject to inductive action when made single conductor. The magnetic field may become strong enough to induce an appreciable difference of potential between the lead sheaths of single-conductor cables of a circuit and cause a flow of current sufficient to cause injury to the lead sheaths where they are in contact with each other. This can be prevented by the use of a jute covering over the lead sheath, though this is found objectionable in case repairs are necessary, owing to the tendency of such cables to stick in the duct. The preferable method with cables of 350,000 c.m. and smaller is to use a multiple-conductor cable. Short pieces of single conductor may be spliced into the main at the manholes where service taps are to be made to facilitate such connections. The saving in first cost due to the use of the three-conductor cable compensates partly for the expense of making the extra splices.

Transmission lines, which are usually three-phase, are of three-conductor cable with a thickness of insulation on each conductor sufficient for the voltage between phases. Another layer is placed over all three conductors as shown in Fig. 148.

Sector Type Cables. — In the larger systems where the conditions of urban transmission require that the carrying capacity of cables be as great as possible and where the diameter of duct systems is fixed at 3 to $3\frac{1}{2}$ inches inside, the ability to increase conductor sizes in high-tension cables is limited by the size of the duct. With the usual round type of conductor this limit is considerably too small at 6600 volts, and is reached in some cases where the voltage is as high as 13,200.

The most available source of relief in such cases is found in the use of conductors having a cross-section shaped like a sector of a circle as in Fig. 149 instead of the usual circular cross-section. This arrangement makes use of space which

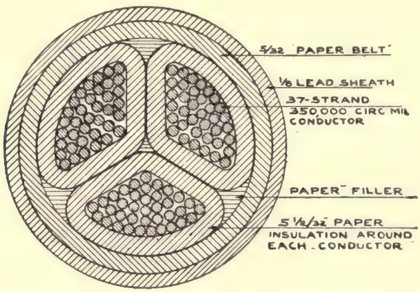


Fig. 149. Cross-section of 9000-volt, 350,000-c.m. Sector Cable.

is ordinarily filled with jute to round out the cable for additional copper. The result is that the conductors may be given a cross-section which is 50 to 100 per cent greater for a given outside diameter. In Fig. 150 are shown curves by which the comparison may be made directly. These curves show the external diameter of round and sector type cables having various conductor sizes up to 600,000 c.m.

The superior facilities afforded by the shape of the sector conductor for the radiation of heat give such cables an increased current carrying capacity as compared with round cables. In round cables the current density (amperes per 1000 circular mils) decreases as the size of cable increases. This is also the case with sector cables but the rate of decrease is less rapid. Thus if a 250,000-c.m. round cable is loaded to its safe temperature when carrying 250 amperes continuously, a sector cable of the same external diameter having conductors of 450,000 c.m. section, will carry current in direct proportion to

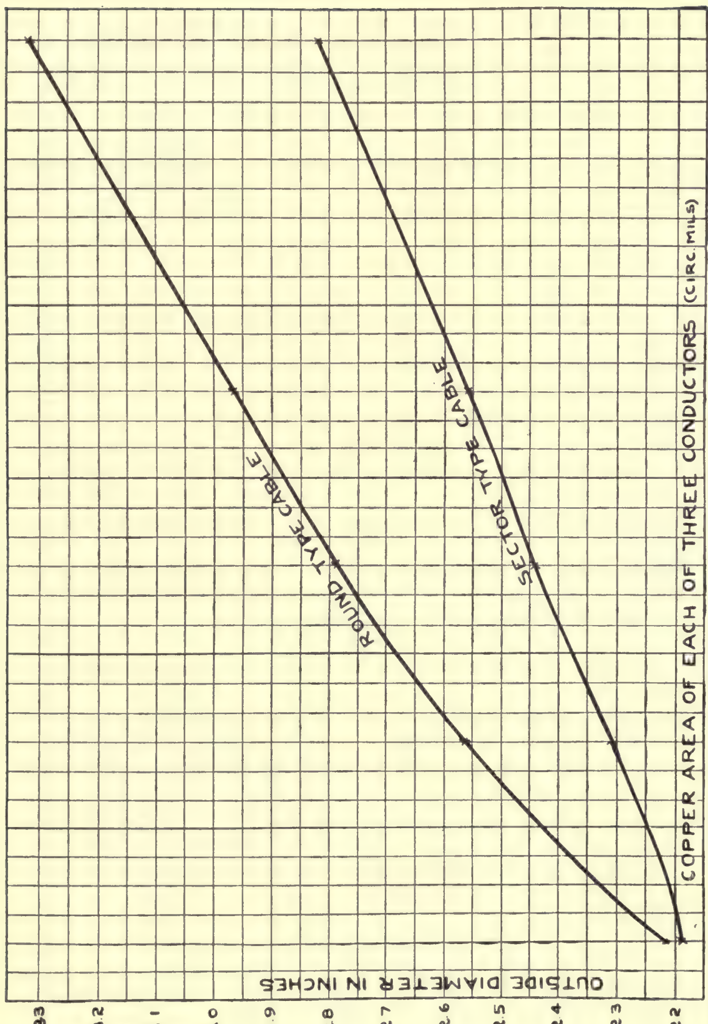

ROUND TYPE CABLE
SECTOR TYPE CABLE
COPPER AREA OF EACH OF THREE CONDUCTORS (CIRC. MILS)
OUTSIDE DIAMETER IN INCHES
100,000
200,000
300,000
400,000
500,000
600,000
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3

Fig. 150.

the increased section at approximately the same temperature. That is, it will carry $\frac{45}{25} \times 225 = 405$ amperes.

In the sizes 250,000 c.m. and larger the cost per foot of sector cable is less than that of round cable of equal conductor section, and the cost per kw. of carrying capacity is considerably less because of the increased capacity per circular mil.

This tends to favor the use of sector cables even where the diameter of ducts is not a limiting condition, as in the case of submarine cables and in the sizes from 200,000 to 300,000 circular mils, which are not too large for standard ducts at voltages below 15,000. The use of sector cables is therefore increasing in the larger systems, where larger cables are found desirable as the capacity of substations is increased from year to year.

Insulation. — Cables are insulated according to the voltage for which they are intended, and to the conditions of installation and maintenance while in service.

Three kinds of insulating material are in general use, (*a*) rubber, (*b*) oiled paper and (*c*) varnished cambric.

Rubber was first used because of its ability to withstand moisture and its elasticity in bending and training cables around corners of manholes and into the ducts, junction boxes, etc. It served its purpose very satisfactorily during the earlier stages of the art of electrical distribution and is still used for many purposes. With the introduction of voltages above 2500, it was found, however, that rubber was affected by the presence of static charges and had a tendency to gradually lose its insulating qualities. This, together with the comparatively high cost of good rubber, led to the development of cable insulation of strips of oiled manila paper wrapped spirally about the cable with sufficient surplus of oil to keep the paper saturated continuously. The number of layers was made

sufficient to give proper dielectric strength for the higher voltages and proper mechanical strength for bending at the lower pressures.

This type of cable insulation has come to be standard for high voltage transmission and feeder cables instead of rubber as it has a high dielectric strength and is less expensive than rubber. It is important that it be protected well at terminals by suitable pot heads and at joints by water-tight sleeves, as it absorbs moisture if exposed.

The dielectric strength depends somewhat upon the quality of the paper and upon the character of the oils used for its impregnation. These oils must be present in ample quantity to prevent sections of cable which may be at a higher level from becoming "dry."

Paper insulation is capable of withstanding higher temperatures than rubber, without injury, which gives it an advantage for low-tension feeders where overloads are likely to be encountered in parts of the system at certain seasons.

Cambric insulation was developed originally for winding of coils of electrical machinery and its usefulness there led to its use in bus-bar insulation and thence to cables. It is made by passing lengths of cambric cloth through a bath of insulating varnish and thence over a series of drying rolls. These lengths, several feet in width, are then cut into strips of suitable width to serve as tape. In this form it is applied spirally to cables to the required thickness for the intended voltage, the layers being held from unwrapping by a plastic compound applied between them.

The cambric forms a somewhat more elastic insulation than paper and is less susceptible to moisture while exposed. It is somewhat more expensive than oiled paper but less expensive than rubber. It has replaced rubber in some classes of work where joints are numerous and exposure to moisture in wet manholes is frequent. The presence of the compound be-

TABLE VIII.—WEIGHTS AND DIAMETER OF SINGLE-CONDUCTOR, PAPER AND LEAD COVERED CABLE, 600 VOLTS.

Size B. & S. and Edison.	Thickness of paper.	Diameter in inches, over			Weights in lbs. per foot.	
		Copper.	Paper.	Lead $\frac{4}{32}$ in.	Copper.	Total copper, paper, lead.
6	$\frac{4}{32}$	.180	.430	.680	.085	.922
4	$\frac{4}{32}$	.234	.484	.734	.140	1.069
2	$\frac{4}{32}$	.295	.545	.795	.224	1.256
0	$\frac{4}{32}$	.378	.628	.878	.338	1.920
00	$\frac{4}{32}$	.425	.675	.925	.426	2.111
000	$\frac{4}{32}$	.475	.725	.975	.532	2.326
0000	$\frac{4}{32}$	.524	.774	1.024	.650	2.551
200	$\frac{4}{32}$	.505	.755	1.005	.614	2.473
250	$\frac{4}{32}$	.568	.818	1.068	.790	2.786
300	$\frac{5}{32}$	.637	.949	1.199	.949	3.243
350	$\frac{5}{32}$	.680	.992	1.242	1.092	3.484
400	$\frac{5}{32}$	.735	1.047	1.297	1.224	3.738
450	$\frac{5}{32}$	.777	1.089	1.339	1.343	3.949
500	$\frac{5}{32}$	.820	1.132	1.382	1.550	4.251
600	$\frac{5}{32}$	.900	1.212	1.462	1.874	4.752
750	$\frac{5}{32}$	1.020	1.332	1.582	2.331	5.473
800	$\frac{5}{32}$	1.037	1.349	1.599	2.462	5.642
900	$\frac{5}{32}$	1.096	1.408	1.658	2.815	6.126
1000	$\frac{5}{32}$	1.157	1.469	1.719	2.138	6.583
1250	$\frac{5}{32}$	1.296	1.608	1.858	3.831	7.584
1500	$\frac{6}{32}$	1.412	1.787	2.037	4.681	8.969
2000	$\frac{6}{32}$	1.652	2.027	2.277	6.237	11.077
2500	$\frac{7}{32}$	1.848	2.285	2.535	7.674	13.221

tween layers assists in preventing the spread of moisture through the cable in case there should be pinholes in the lead.

The thickness of insulation is determined by considerations of both mechanical and dielectric strength. The bending of cables in manholes and at service entrances places a strain on the insulation which it must be able to withstand without materially affecting its dielectric strength. The tape which forms the insulation must therefore be applied in several overlapping layers to prevent injury. There is also a limit to the radius of bending which should not be exceeded, which is from 6 to 8 times the diameter of the cable.

With low-tension cables, that is 600 volts and under, the minimum thickness which is safe for bending is adequate

TABLE IX. — SINGLE-CONDUCTOR CABLES.

VARNISHED CAMBRIC INSULATION.

Size A. W. G.	3000 volts.		5000 volts.		7000 volts.		13,500 volts.	
	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.
6	642	.57	817	.70	904	.76	1,717	1.11
4	748	.62	927	.75	1,228	.84	2,138	1.19
2	893	.68	1,378	.84	1,389	.90	2,294	1.24
1	994	.72	1,392	.88	1,506	.94	2,431	1.28
0	1108	.76	1,521	.92	1,637	.98	2,582	1.33
00	1447	.84	1,676	.96	1,804	1.03	2,765	1.37
000	1627	.89	1,860	1.02	1,981	1.08	2,970	1.42
0000	1843	.95	2,083	1.07	2,488	1.17	3,233	1.48
250,000	2026	1.00	2,548	1.15	2,690	1.22	3,451	1.53
300,000	2278	1.05	2,822	1.21	2,965	1.27	3,731	1.59
350,000	2489	1.10	3,048	1.26	3,194	1.32	3,975	1.63
400,000	2987	1.18	3,278	1.31	3,428	1.37	4,636	1.71
500,000	3442	1.27	3,743	1.39	3,893	1.45	5,141	1.80
600,000	3888	1.35	4,197	1.47	4,038	1.53	5,636	1.88
650,000	4100	1.39	4,414	1.51	4,429	1.58	5,880	1.92
700,000	4322	1.42	4,632	1.55	5,026	1.64	6,122	1.95
750,000	4531	1.45	4,853	1.58	5,254	1.67	6,350	1.98
800,000	4735	1.48	5,444	1.64	5,479	1.70	6,572	2.01
900,000	5066	1.56	5,825	1.72	5,787	1.78	6,955	2.09
1,000,000	5970	1.64	6,412	1.77	6,092	1.83	7,495	2.17
1,250,000	....	....	7,429	1.92	6,846	1.99	9,303	2.36
1,500,000	....	....	8,388	2.02	7,825	2.09	10,319	2.46
1,750,000	....	....	10,056	2.20	9,535	2.29	11,524	2.60
2,000,000	....	....	11,070	2.30	10,483	2.36	12,471	2.68

for dielectric strength. In the sizes of such single conductor cables up to 250,000 c.m. it is usual to provide $\frac{1}{8}$ inch of paper or cambric insulation. The larger sizes require $\frac{5}{32}$ to $\frac{7}{32}$ inch as indicated in Table VIII, to give proper mechanical strength. This table also shows the weights and diameters of copper and lead in single-conductor cables.

With cables designed for use at higher voltages, additional thickness is required to provide suitable dielectric strength.

There is some variation in practice among engineers as to the thickness provided per kilovolt, due to different ideas as to the necessary factor of safety, but experience has indicated that, for 2200-volt distribution, single-conductor

cables up to 4/0 A. W. G. are satisfactory in operation with $\frac{5}{32}$ inch insulation.

Cables for 6600 volts have about $\frac{6}{32}$ inch insulation and those for 15,000 volts, about $\frac{10}{32}$ inch.

In three-phase systems, operating without the neutral point of the transmission system grounded, the thickness of insulation should be somewhat more than with grounded neutral systems since the strains are greater in the ungrounded system under certain conditions.

TABLE X. — THREE-CONDUCTOR CABLES.

RUBBER INSULATION.

Size A. W. G.	3000 volts.		5000 volts.		7000 volts.		13,500 volts.	
	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.
6	1567	.918	2144	1.188	3077	1.490	4437	1.960
4	1889	1.022	2499	1.292	3488	1.594	4885	2.064
2	2358	1.152	3354	1.453	4046	1.723	6535	2.256
1	2847	1.314	3760	1.548	4471	1.818	6995	2.351
0	3217	1.398	4134	1.633	5769	1.965	7523	2.436
00	4045	1.524	4636	1.727	6342	2.060	8133	2.530
000	4619	1.635	6108	1.900	7013	2.170	8848	2.641
0000	5318	1.759	6893	2.026	7823	2.295	9736	2.766

PAPER INSULATION.

Size A. W. G.	3000 volts.		5000 volts.		7000 volts.		13,500 volts.	
	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.	Weight per 1000 ft.	Diameter over lead.
6	1874	.979	2190	1.114	3199	1.508	5,742	2.100
4	2270	1.083	2597	1.218	3646	1.608	6,299	2.206
2	2837	1.213	3188	1.345	4274	1.740	7,052	2.335
1	3405	1.314	3583	1.441	4705	1.837	7,561	2.433
0	3864	1.459	4045	1.525	6110	1.984	8,144	2.515
00	4420	1.553	4610	1.622	6755	2.080	8,841	2.608
000	5081	1.663	6106	1.795	7513	2.190	9,657	2.720
0000	6700	1.852	6978	1.919	8446	2.315	10,663	2.845

In general, rubber cables are used where the insulation is frequently exposed for jointing and where electrolytic or other conditions cause damage to the lead sheath at intervals. Distributing mains are quite commonly of rubber cable for these reasons, while feeders and transmission lines are usually made up of paper cable.

The insulation provided for cables in use in some of the large transmission systems is shown in Table XI. It will be noted that the thickness of insulation varies from 67 mils per 1000 volts between conductors at 6600 volts to 22 mils at 25,000 volts and from 52 mils per 1000 volts between conductor and ground at 6600 volts to 16 mils at 25,000 volts. These differences are due in part to differences of opinion as to what factor of safety should be used in the design of high-potential cables. The lower values of thickness are used on the higher voltages because the thickness required does not vary directly with the voltage.

For pressures above 20,000 volts, the design of cable insulation should be based on the principle that the most rapid fall of potential takes place in the layers of insulation next to the conductor. It is well established that the outer ring of insulation in a triplex cable adds comparatively little to the dielectric strength of the whole insulation, and that the layers on the individual conductors bear most of the burden. The outer layers are of assistance as additional protection from moisture in case of a break in the sheath and in bending.

In the case of cables operating at 20,000 to 30,000 volts it has therefore been the practice in most cases to use a "graded" type of cable, that is a cable with one insulating medium of high value next to the copper, and another medium for the outer layers. The result is a cable which has a sufficient dielectric strength with materially less thickness of insulation than would be required if it were all of one type. This is important in these high voltage cables since otherwise the over-all diam-

TABLE XI. — INSULATION OF VARIOUS THREE-CONDUCTOR, HIGH-TENSION, CABLE INSTALLATIONS.

Name.	Working voltage.	Neutral grounded.	Size of conductor B. & S. or C. M.	Insulation.	Thickness of insulation. In 64ths of an inch.		Thickness of insulation. Per 1000 volts in thousandths of an inch.	
					About each conductor.	Jacket.	Between conductors.	To ground.
Brooklyn Rapid Transit Co.	6,600	No	250,000	Paper	13	10	61	54
New York Edison Company.	6,600	No	250,000	Paper	10	10	47	47
Cataract Power & Conduit Co.	11,000	No	000	Paper	13	13	37	37
Interborough Rapid Transit Co.	11,000	Yes	000	Paper	14	14	40	69
N. Y. C. R. R.	11,000	Yes	0000	Paper	14	12	40	64
Minneapolis Rapid Transit Co.	13,000	Yes	3	Paper	12	12	29	50
Philadelphia Rapid Transit Co.	13,200	No	00	Paper	12	12	28	28
Baltimore United Railways.	13,200	Yes	000	Paper	14	10	33	49
Commonwealth Edison Co.	20,000	Yes	00	Paper	18	12	28	41
Detroit Edison Co.	23,000	Yes	2	Cambric	12	6	22	26
St. Paul Gas Light Co.	25,000	No	2	Paper	18	8	22	16
Shawinigan Power Co.	25,000	No	00	Rubber	28	none	17	17

eter reaches the capacity of a $3\frac{1}{2}$-in. duct in sizes of conductor which are too small for economy of duct space and cable investment.

Current-carrying Capacity. — In low-tension distribution, in underground transmission cables and in other situations where the size of the conductor is not determined by the permissible line drop, the size of the conductor is usually fixed by the heating of the cable under normal loads.

If the voltage and distance are such that the permissible

line drop is reached only with a volume of current which produces dangerous heating of the insulation, then the capacity of the cable is fixed by the ability of the insulation to withstand heat and not by the line drop. In general, this is the case when the distance of transmission is less than one mile per 1000 volts of working pressure. In a low-tension system at 230 volts, this limit is reached at about .23 mile, or 1200 feet. In a three-phase transmission cable at 10,000 volts, the line drop becomes the determining factor at distances over 10 miles. However, with conductors of less than 500,000 c.m. single conductor or 4/0 three conductor, the heating limit is higher than with larger cables, because of greater radiating surface per watt of energy dissipated.

The safe carrying capacity of lead-sheathed cables in underground conduit is fixed by (*a*) the number of watts dissipated per foot of conduit, (*b*) by the radiating capacity of the conduit and cable, and (*c*) by the ability of the cable insulation to withstand high temperatures.

The number of watts dissipated per conduit foot is in turn fixed by the number of cables, by the load they carry and by the cross-sectional area of the conductors. The radiating capacity of the conduit system varies somewhat with the arrangement of the ducts. A square duct section which happens to be the most economical to construct is unfortunately the least effective in heat radiation, since its contact area with the surrounding earth is the least of any rectangular section. The radiation of heat from the inner ducts must pass through the outer ducts and cables to get to earth. This raises the temperature of the entire duct system, since the heat dissipated from the inner ducts has a path of greater resistance and the temperature gradually increases until the radiation equals the amount of heat liberated. This requires about 8 hours in 12 to 20 duct systems at constant load on the cables.

With lines having less than 9 ducts there is little difficulty but in large lines the increased temperatures may make an appreciable reduction in the carrying capacity of the cables, if a safe temperature limit is respected.

H. W. Fisher made a study of this effect in a large duct system at Niagara Falls which led him to the conclusion that the capacity of the cables in the inner ducts of a large duct line was reduced to from 60 per cent to 80 per cent of their capacity under similar loading in a small duct system.

It does not follow that duct systems of over 9 ducts should be entirely avoided however, as this reduction in capacity is only found where there are more than about 10 ducts full of cables operating at loads which cause heating. Where a part of the duct run is occupied by high tension or other cables which are not normally warm, it is good practice to build duct lines as large as 24 to 30 ducts.

The effect is illustrated by a test made on a low-tension direct-current feeder in Chicago, results of which are shown graphically in Fig. 151. This feeder was in large duct lines near the substation and consisted of two 1,000,000 c.m. cables in separate ducts. It was operated at approximately constant loads, as indicated for periods of eight hours. The temperature of the lead sheath plainly follows the air temperatures in the manholes and is appreciably higher in those portions of the line where there are the greatest number of cables operating at temperatures above that of the air.

The carrying capacity of multiple-conductor cables is smaller than that of similar single-conductor cables under similar conditions. The energy dissipated by three conductors under a given loading is the same whether they are in single cables or grouped in a three-conductor cable. The area of radiating surface of the three-conductor cable is, however, materially less than the aggregate area of the radiating surfaces of the single-conductor cables. The result is a greater rise of temper-

ature in the three-conductor cable and a reduced carrying capacity at the maximum safe temperature of the insulation. Duplex cables thus lose about 10 per cent, and two-conductor concentric cables about 20 per cent of their capacity

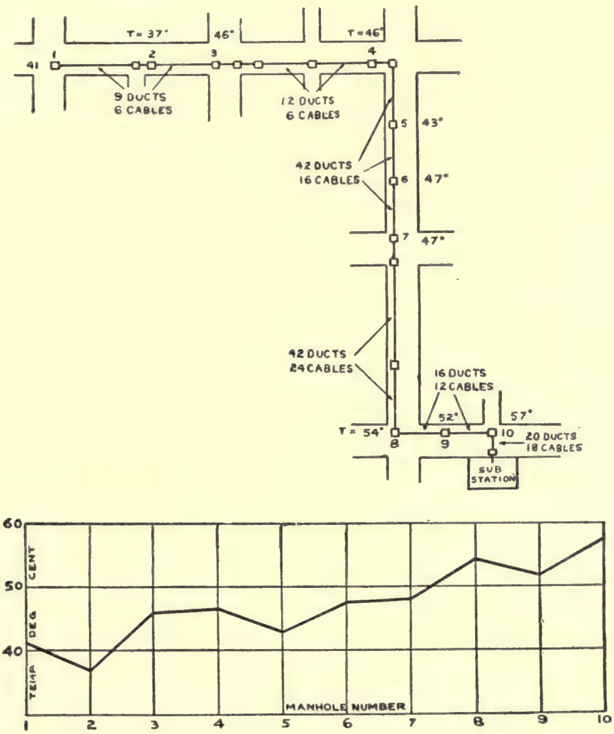


Fig. 151. Rise of Temperature in Cable Sheath.

as single cables. Triplex cable loses about 25 per cent and three-conductor concentric cable even more of its capacity.

The permissible current density, expressed usually as the number of amperes per 1000 circular mils, varies with the size of the conductor. A small cable may be loaded more economically as regards the weight of copper per kw. than a larger cable. This results from the fact that the area of the conductor

increases as the square of the diameter while the area of the radiating surface increases in direct proportion to the diameter. Thus if the diameter of a conductor is doubled, its cross-sectional area and current-carrying capacity are made four times as great, while the radiating surface available for the dissipation of heat is only doubled. Hence the production of heat in the cable very rapidly overtakes the capacity to radiate it, as the size is made larger and it is necessary to gradually reduce the current density as larger sizes of cable are approached. This reaches a point where the use of copper is so inefficient that it becomes more economical to use two or more cables of a smaller size to secure the required capacity. This is frequently done where sizes above 1,000,000 c.m. would otherwise be required.

However, with cables in conduit systems on crowded streets, the cost of the ducts and the difficulty of securing sufficient duct space often leads to the use of cables of 1,500,000 c.m. and in some cases 2,000,000 c.m. in low-tension distributing systems.

The current density of the sizes of conductors used in distribution work may therefore be made about 2 amperes per 1000 c.m. in No. 6 or No. 4 cables without dangerous heating, while in a 1,000,000 c.m. cable it is about .75 ampere for loads lasting more than two to three hours. The density at the time of the maximum load may, of course, be run appreciably higher than these figures, in cases where the peak of the load is of less than two hours duration.

Temperature Limits. — The limit of current density is fixed by the ability of the cable insulation to withstand high temperatures. This, in turn, depends upon the character of the insulation.

Rubber insulated cables should not be operated for any considerable time at temperatures above 50 degrees C. as the

rubber loses its resilience and strength if frequently heated more than this. Oiled paper and varnished cambric may be operated as high as 75 degrees C. without danger of injury. However, while heating above these limits is injurious if continued regularly, these temperatures may be exceeded for a number of hours during an emergency without serious injury.

With cables operating at pressures above 6600 volts, the heating is affected by the dielectric loss in the insulation.

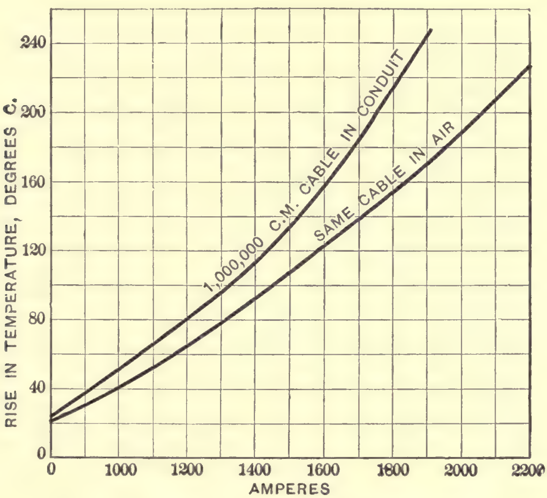


Fig. 152. Heating of Single-conductor Cable.

This loss increases as the temperature increases and adds appreciably to the temperature of the cable at temperatures of 50 degrees C. and higher.

Tests reported by L. A. Ferguson in his paper before the International Electrical Congress at St. Louis in 1904 furnish very useful data as to the temperatures attained in paper-insulated cables laid in underground conduits. Fig. 152 shows the rise in temperature experienced by a 1,000,000 c.m. single-

conductor cable, in tile duct and in air, after carrying loads from 800 to 1900 amperes for 3 hours or more. It will be noted that at a load of 1000 amperes the rise of temperature of the cable in the air is 41 degrees C., while in conduit it is about 10 degrees C. higher.

The results represented by the curve in Fig. 153 show the rate of rise of temperature in a two-conductor concentric cable

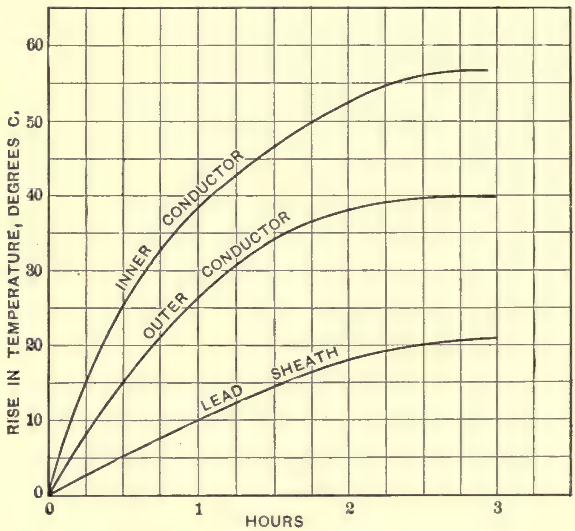


Fig. 153. Heating of Concentric Cable.

of 1,000,000 c.m. in each conductor when it is carrying 1000 amperes. It is apparent from the curves that the temperature of the outer conductor is practically the same as that of the single-conductor cable of the same section in air, but that the inner conductor runs hotter. The rate of rise is such that the ultimate elevation of 40 degrees in the outer conductor is reached in about $2\frac{1}{2}$ hours, 70 per cent of this rise having occurred in the first hour. Overloads of short duration may therefore be carried safely. Data for a three-conductor cable

of 4/0 in conduits are given in Fig. 154 for various ampere loads. This cable was loaded with an equal current in each conductor, and it is apparent that with equivalent current densities this cable runs cooler than the 1,000,000 c.m. cable. This is due to the fact that the radiating surface of the three-conductor cable is over 60 per cent greater than that of the single-conductor 1,000,000 c.m. cable.

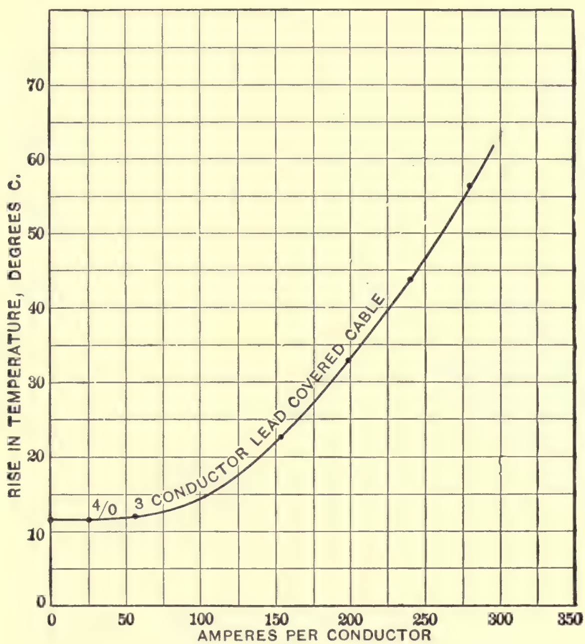


Fig. 154. **Heating of Three-conductor Cable.**

The loss on a cable is preferably expressed in watts per duct foot, as the heating of cable and air is directly proportional to this quantity.

The resistance of a 1,000,000 c.m. cable being .0000124 ohm per foot at 50 degrees C., the energy loss, C^2R, in a single-conductor cable at 1000 amperes is 1000 × 1000 × .0000124 = 12.4 watts. Likewise in a 1,000,000 c.m. concentric cable

the loss is 24.8 watts per foot. In a three-conductor 4/0 cable, with 200 amperes current on each conductor, the resistance per foot being .00006, the loss per foot of cable is $3 \times 200 \times 200 \times .00006 = 7.2$ watts. With smaller conductors the energy loss is less for a given current density, and the surface of radiation not decreasing proportionately, the current density may be run higher.

Temperature and Current Relations. — The temperature of the conductors of a cable may be calculated approximately for a given current, if the kind and thickness of its insulation are known. Various empirical formulæ have been developed from tests by European and American investigators. The most available of these for use in a cable distribution system are those by which it is possible to derive the copper temperature from thermometer readings taken on the outside of the lead sheath.

Atkinson and Fisher give the following useful formulæ in a paper presented before the American Institute of Electrical Engineers in 1913:

The rise in temperature of copper above lead in a single conductor oiled paper, or varnished cambric lead covered cable is

$$t' = 270 \log \left(\frac{d'}{d}\right) \frac{I^2}{\text{c.m.}},$$

where d' is the diameter over the insulation, d is the diameter of the conductor, I is the current and c.m. represents the circular mils in the conductor. The constant 270 must be increased to 300 for three-conductor cables having relatively large proportions of insulating material as compared with the amount of copper.

For low-tension conductors having a larger proportion of copper, the constant may be as high as 330. With three-

conductor cables, the value of d must be taken as the diameter of the circle, circumscribed about the three conductors including their individual insulation, and the final result must be multiplied by 3.

The rise of temperature of the lead above air is

$$t' = \frac{110\,I^2}{D \times \text{c.m.}} \text{ degrees Cent. for a single-conductor cable,}$$

when D is the outside diameter of the lead sheath. For a three-conductor cable, multiply the result by three.

The value of the coefficient 110 varies somewhat with the size of the cable, being lower for the smaller sizes of single-conductor and higher for the larger sizes and for multiple-conductor cables. It also tends to be reduced as the lead sheath becomes darkened and rougher by age and exposure.

For instance with a 250,000 c.m. single-conductor cable, the values are found thus: Assume $d = .575$ in. and $d' = .95$ in. $D = 1.14$ in.

The temperature rise at 200 amperes from lead to copper is

$$t' = 270 \log\left(\frac{.95}{.575}\right)\frac{200 \times 200}{250{,}000} = 9.4 \text{ degrees C.}$$

The rise in temperature from air to lead sheath is

$$t' = \frac{110 \times 200 \times 200}{1.14 \times 250{,}000} = 15.5 \text{ degrees C.}$$

With a manhole temperature of 20 degrees C. the cable sheath would be $20 + 15.5 = 35.5$ degrees and the copper would be $35.5 + 9.4 = 44.9$ degrees.

If the thermometers were placed on the sheath of the cable in a suitable way to correctly record the sheath temperature it would be safe to assume that for a cable of this type the copper temperature would be higher than the lead sheath was found to be by an amount equal to $\frac{9.4}{15.5} = 60$ per cent of the

temperature rise of the sheath above the manhole air. This ratio will apply at all loads which it is safe for the cable to carry.

In the case of a three-conductor 250,000 c.m. cable having values of $d = 2.04$ inside diameter of the over-all insulation, $d' = 2.29$ outside diameter of insulation and $D = 2.54$ diameter over lead.

$$t' = \frac{3 \times 110 \times 200 \times 200}{2.54 \times 250{,}000} = 20.7 \text{ degrees C. lead above air,}$$

$$t' = 3 \times 300 \log \left(\frac{2.29}{2.04}\right) \frac{200 \times 200}{250{,}000} = 7.2 \text{ degrees C. copper}$$

above lead.

With an air temperature of 20 deg. C. the sheath temperature would be $20 + 20.7 = 40.7$ and the copper temperature would be $40.7 + 7.2 = 47.9$ deg. C.

In this cable the copper temperatures would be $\frac{7.2}{20.7} = 35$ per cent of the rise of the lead above air, above the sheath temperatures as registered by a thermometer.

Selection of Ducts. — In placing cable in the duct system a uniform method of selecting ducts should be followed as far as possible. The cable of a through line should occupy the same relative position throughout its course as far as this is possible. Cables used in local distribution should be given a uniform place in the duct system, preferably in the top row, so that handholes can be built between manholes for service laterals without sinking them below the top row of ducts. The lower ducts are thus left for through lines which may be trained through the manholes below junction boxes, fuse boxes, etc., which it is desirable to mount on the walls of the manholes.

Ducts should be selected for through lines so that they may

be trained with the least interlacing with other cables. Lack of attention to this detail may result in a tangled condition which increases the danger to other cables and greatly impedes any repair or reconstruction work which may become necessary.

Routing of Lines. — Through lines should be so routed as to utilize duct lines to the best advantage. When a duct is taken for a through line on a given street it should follow that route as far as possible, as the corresponding duct on the remainder of the street is blocked for use on through lines going elsewhere.

The continuity of the service is better assured if transmission lines are separated wherever possible. This can be done by routing lines running to the same substation through different conduits. The two arrangements shown in Figs. 155 and 156 supply a group of six substations with duplicate lines to each. In Fig. 155 the amount of duct line is a minimum but the risk is a maximum, while in Fig. 156 ducts in the distributing conduit lines on other streets are used with the maximum of protection from interruption of service due to cable trouble.

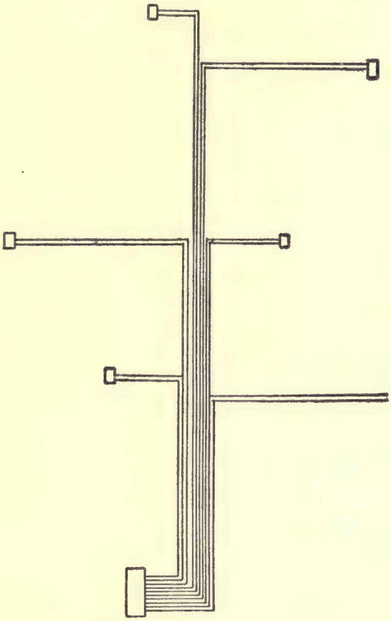


Fig. 155. Lines Routed in Same Duct Lines.

Installation of Cable. — Cables are drawn into ducts by means of a line attached to a source of power. This line is put

through the duct by the use of detachable rods of wood about three feet long and one inch in diameter, which are pushed into the duct as they are joined together. They are then drawn through with the pulling line attached and disjointed as

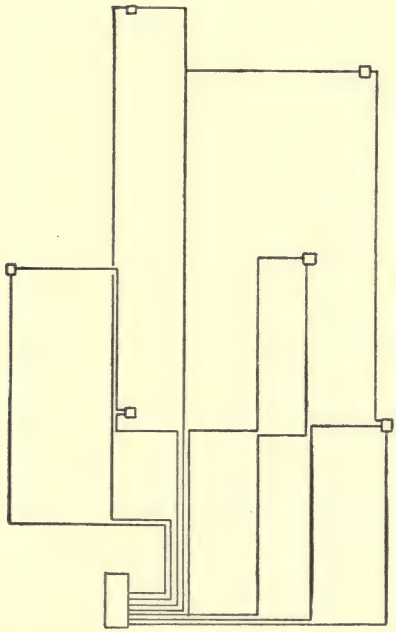


Fig. 156. Lines Routed in Different Duct Lines.

they come through. The cables are secured to the pulling line by baring the copper and making a secure mechanical connection or by means of patent cable grips, which are more quickly attached and removed, and save considerable time.

When the cable pulling line is ready for use, it is run over pulley wheels out of the manholes and to the source of power. The reel of cable is set up so that it will revolve and pay out cable as it is drawn in. Enough men are placed at the reel and in the manhole to guide the cable into the duct and pre-

vent its sheath being injured, as it passes through the manhole opening.

Power is supplied for pulling in various ways. With short runs and small cable a few men can draw the cable in. With runs of 300 to 500 feet the most general power is a capstan manned by 4 to 6 laborers, as in Fig. 157. In the large cities where many heavy cables are being pulled, in long runs, an automobile truck has been used to advantage, the speed being reduced by block and tackle and by running the truck at slow speed. This permits of work being done more rapidly than with a capstan.

Where several cables are to be drawn into one duct they should be installed simultaneously by securing them to one line, as the duct cannot be utilized as fully as it should if it is attempted to pull them separately. Four single-conductor cables of any size up to No. 4 A.W.G. can be drawn into a square $3\frac{1}{2}$-inch duct without danger of injury.

Small cable is put up on reels and cut to fit as it is drawn in, but a length of about 400 feet of three-conductor high-voltage cable or of 1,000,000 c.m. feeder cable fills a reel. It is therefore usual to order such cable in specified lengths. The distance from center to center of manholes plus the amount needed for training around the walls of the manhole and splicing is the length to be ordered. The reels are marked for delivery at certain street intersections and with the length of cable which they contain. It is important that such lengths be determined within a few feet, as all short ends cut off by the jointer are of value only as junk, and may represent a considerable sum of money on a large job, where the cable costs from \$1.00 to \$2.00 per foot.

Training Cables. — The training of cable through manholes must be done carefully to avoid sharp bends, tangled relations with other cables and possibility of injury due to exposure to

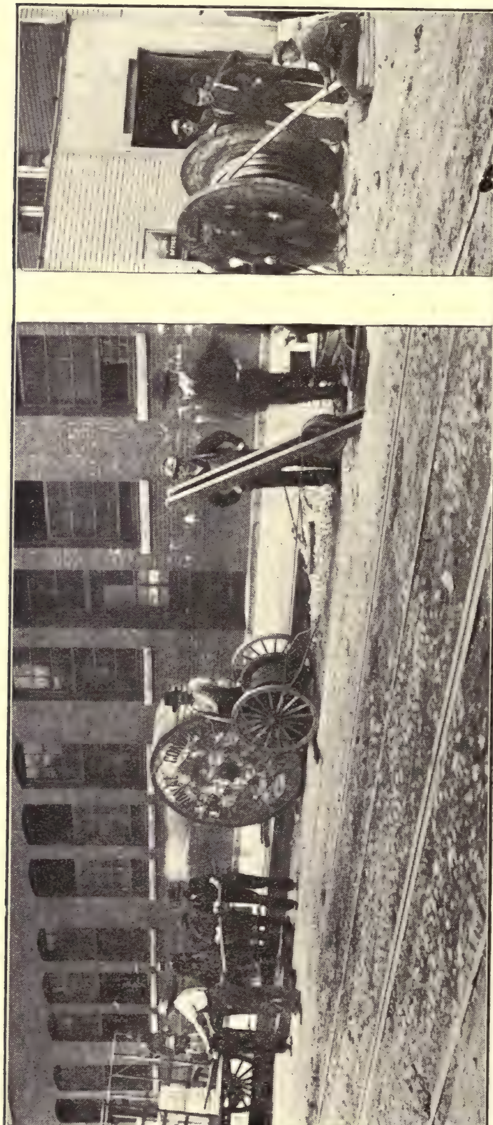


Fig. 157. Drawing in Cable by Capstan.

workmen's shoes while working in the manhole. It is customary to support cables on iron racks hung on the brickwork of the walls. In some cases, brickwork shelves are built around the walls, on which the cable is laid. In some large systems the important cables are laid in split tile ducts carried on shelves around the sides of the manhole.

Where high-voltage cable is carried through manholes on iron racks without protection, the failure of the cable at one point is apt to charge the lead sheath and cause it to be damaged in adjacent manholes where the current attempts to pass from the lead to ground through the iron racks. It is usual to protect cables in manholes to prevent the communication of trouble to other cables. This is done by wrapping them with asbestos tape or some similar fireproofing material, or by the use of split tile or brick shelving as described above. Manila rope plastered with cement has been found to be very satisfactory for this purpose. Where lines are carrying important light and power service the extra cost of the protection is amply justified.

With paper and cambric cables particularly and with other cables as well, the radius of bends must not be made too small. The shape of the manhole walls and the manner of bringing the ducts into the walls should be designed with this in view. The radius of a bend should not be less than 8 or 10 times the diameter of the cable. This is one of the chief limitations in the use of heavy concentric and multiple-conductor cables whose diameter is so great that they can only be trained through manholes with considerable difficulty. In case of changes which necessitate the withdrawal of cable, the larger sizes may be ruined in passing over the idler wheels as the cable emerges from the manhole, due to the necessarily small radius at which it is bent. It is therefore necessary to use means of pulling out such cable without subjecting it to strain in passing over the idlers.

Cable Jointing. — As soon as the lengths are drawn in the ends should be sealed to exclude moisture, unless they are to be jointed at once. The work of jointing requires the services of an expert, especially with high-tension paper cables. In jointing single-conductor cables the lead sheath is removed five or six inches back from the end of each piece of cable and enough of the copper bared to permit a good soldered connection being made as in any other cable of similar section. After soldering, the bare parts are wrapped with tape of the same material as the insulation until the equivalent of the cable insulation has been applied. A lead sleeve which has previously been slipped back over one of the cables is now wiped on to the two cables so as to enclose the joint. The air spaces around the joint are then filled by pouring hot insulating compound into a small hole in one end of the sleeve until it does not settle down further. A similar hole should be left open in the other end of the sleeve to allow air to escape easily while pouring the compound. The openings in the lead sleeve are then closed by soldering, thus sealing the joint from moisture. The joint should be allowed to cool before it is moved, so that the relative positions of the conductor and insulation inside the joint may not be disturbed. The various operations for a three-conductor cable are illustrated in Fig. 158.

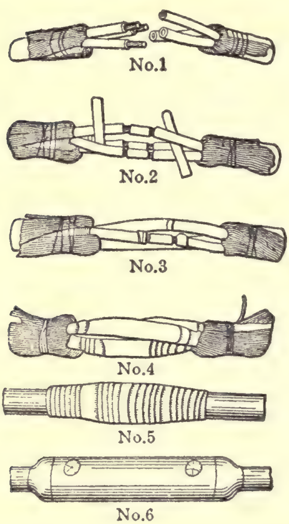


Fig. 158. Process of Making Joint.

In jointing three-conductor cables the lead must be removed about 10 inches back to facilitate the separation of the conductors while the tape is being applied. If any sign of moisture

appears in the ends of the cable, the end of the cable should be cut back until it is eliminated. If this cannot be done without removing too much, it may be necessary to drive it off by heating the cable with a blow torch several feet back from the end. The presence of slight amounts of moisture should be guarded against by pouring hot compound over the bared ends. The compound should be hot enough to boil water, but not so hot as to char a piece of paper. In making joints for voltages of 6600 and higher some special precautions are necessary. It is very important that as little air remain in the taping as possible. If paper tape is used each layer should have compound poured over it before the next is applied. Some cable manufacturers prefer to use a cotton tape for this purpose on account of its absorbent qualities. The lead sleeve must be large enough to slip over the taped joints, and in three-conductor cable the space taken by the joints is such that the diameter of the sleeve must be from 1 inch to $1\frac{1}{4}$ inches more than that of the cable. With single-conductor cable $\frac{1}{2}$ inch to $\frac{3}{4}$ inch more is usually enough. Where a tap is to be taken off, the sleeve may be arranged at right angles in the form of a T, or at a tangent, as a Y joint. The T joint is usually difficult to dispose of on the manhole wall without straining the sleeve, while the tangent form may be trained along with the cable to which it is tapped.

Where single-conductor cables are joined to multiple conductor, the joint is made in a similar manner, the single-conductor cables being flared out slightly, to insure proper separation and to permit the proper wiping of the sleeve.

Such joints are more difficult to make than straightaway splices and require considerable skill. The jointer requires the services of a helper in preparing the lead sleeves, heating solder and compound and guarding the entrance to the manhole. The making of a three-conductor high-tension joint in a paper cable usually requires about 4 hours, two joints a day

being a fair rate of progress in such work. Single-conductor and low-tension cables do not require as long a time.

Pole Terminals. — In primary distributing systems in which part of the lines are underground, there are connections made between underground and overhead lines. It is usual to run feeders and important mains underground for some distance from the station in large cities, connecting them to the overhead lines in the more scattered areas.

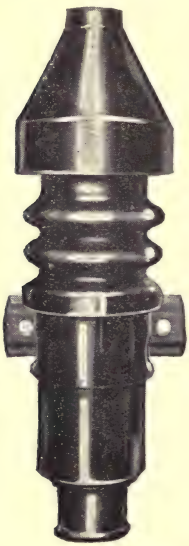


Fig. 159. Detachable Porcelain Pothead.

Where alley distribution is general the main lines are placed underground on streets and the local distributing taps taken off to overhead lines in alleys. In other locations lines must be carried underground across a boulevard, railroad or stream. This class of distribution was for many years very troublesome because of the difficulty of properly caring for the cable ends which are brought up the pole to the overhead lines. Plain joints made by stripping the lead back a few inches and covering with tape and compound were succeeded by wiped lead sleeves filled with compound and left open at the end where the line wire came out. In some cases the joints were protected by enclosing them in wooden boxings. All of these various forms were susceptible to the action of sun and rain.

The problem was quite satisfactorily solved by the development of a type of cable terminals embodying porcelain sleeves into which the conductor of the lead covered cable was brought for attachment to the overhead conductor. The authors developed the first of this type of cable terminal in 1905 to meet conditions which were very troublesome in con-

nection with crossings of single-conductor cable in Chicago. The porcelain sleeve is placed about the end of the cable and equipped with a slip joint by which the cable conductor can

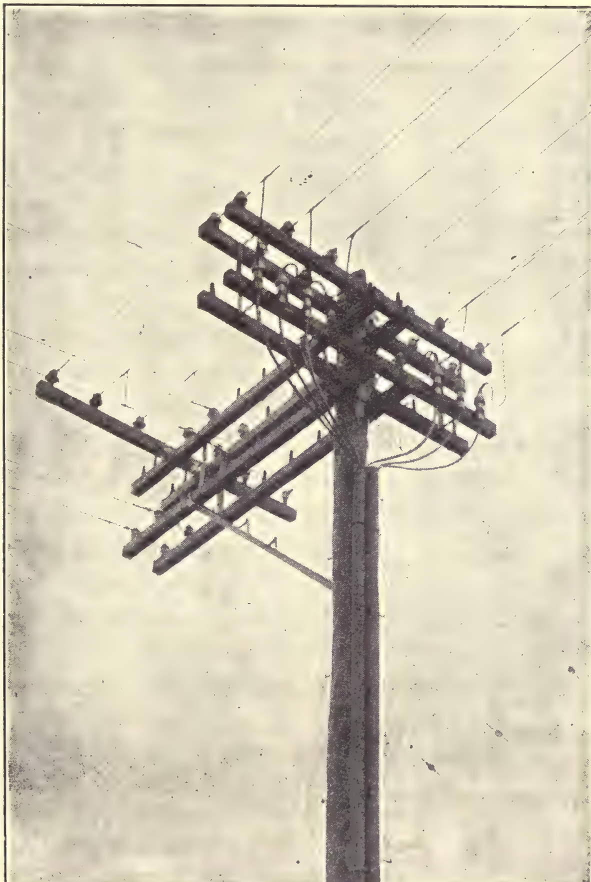


Fig. 160. Installation of Porcelain Potheads.

readily be connected to or disconnected from the overhead conductor, as shown in Fig. 159. The tube is covered at the top by a porcelain cap which serves the double purpose of

protecting the tube from the weather and holding one of the connecting metals. The tube is filled with a suitable insulating compound to protect the cable insulation from moisture and the top of the cap is well taped and painted so that no rain can enter around the overhead wire. An installation of these appears in Fig. 160.

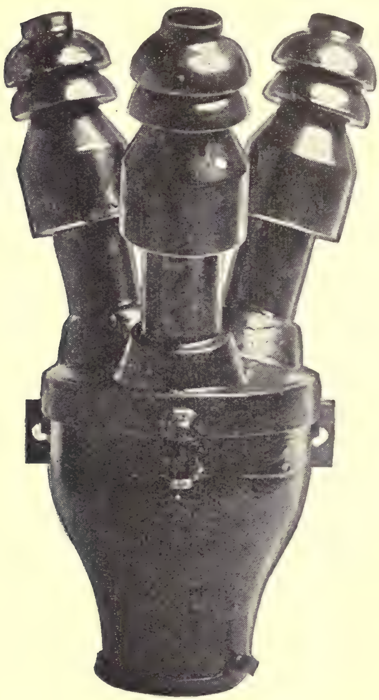


Fig. 161. Porcelain Pothead for Three-conductor Cable.

The factor of safety was so greatly increased by the greater separation made possible by this construction that the trouble from puncture by lightning was entirely eliminated and the cable terminal became as reliable as any other part of the distributing system.

The device, though first designed for single-conductor cables, was later made applicable to multiple-conductor cables of various voltages and for use inside or out of doors, an outside type of three-conductor terminal being shown in Fig. 161.

Transformers and Junction Boxes. — The arrangement of transformers, fuse boxes, junction boxes and similar accessories in manholes should be worked out with care and foresight. Such apparatus should not be so placed in manholes as to obstruct the space needed for cables at a later date or to make a neat and orderly arrangement of cables impossible. It is first of

all important that manholes in which the larger pieces of apparatus, such as transformers or junction boxes, are placed should be of ample size to accommodate them properly.

Transformer installations in manholes involve the use of primary fuse boxes or junction boxes of a suitable type and in case of an interconnected secondary network should be equipped with a network protector, as described in Chapter VII, or a low-tension junction box. With smaller sizes of transformers, the cables are terminated in fuse boxes of the subway type, having wiped sleeve connections.

Where transformers are in manholes which are likely to be flooded during certain seasons, they should be of the subway type. This type is provided with sleeve connections by which wiped joints may be made to the cables and has a water-tight cover.

Low-tension junction boxes for use in manholes are of two types, one of which is mounted on the wall in a vertical position, while the other is placed horizontally in the roof of the manhole with a separate cover, so that it is accessible for replacing fuses or cleaning contacts above ground. The wall type is perhaps the better as regards the training of cables, as they may be kept in order on the walls of the manhole. The surface type, Fig. 87, makes it possible to do maintenance work on the surface which is of some advantage in districts where the traffic is light and the drainage of manholes not perfect, but in a busy street it is preferable to be able to do this work in the manhole where it is not interfered with by traffic or crowds of curious observers.

Emergency Disconnectives. — The primary distributing feeder and mains which are underground must be provided with suitable disconnectives for testing purposes and for the isolation of sections of the mains when additional taps are being connected or repairs are being made. This work can-

not usually be done while the cable is alive and the disconnective junction boxes must therefore be so placed that sections may be taken out of service with as little interruption of supply to consumers as possible.

The mains radiating from a feeder center of distribution should be equipped so that the feeder may be isolated from the mains, or any main can be isolated from its supply. In the case of circuits which are largely underground, the dis-

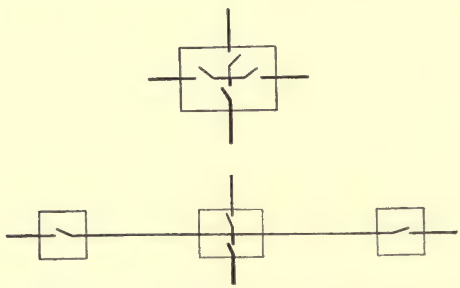


Fig. 162. Arrangement of Disconnectives.

connectives at the feeder terminal must be placed in a manhole. The scheme of connections shown in Fig. 162 is necessary where complete isolation is required. This may be carried out in one manhole, if space is available or in separate manholes, as in the lower sketch, if necessary.

In the case of important large consumers where two sources of supply must be maintained, it is usually preferable to do the transferring on the primary side to save duplicating transformer investment. In such cases a throw-over arrangement as indicated in Fig. 163 is desirable.

In this emergency class of switching there is little occasion to open the circuit under any but very small load. If the service has been interrupted by a breakdown, the load is off entirely. If the switching is done in connection with construction work, it must usually be arranged for an hour when

the load is light and consumers will not be seriously inconvenienced by the switching operations.

For these reasons it is not essential that oil break switches

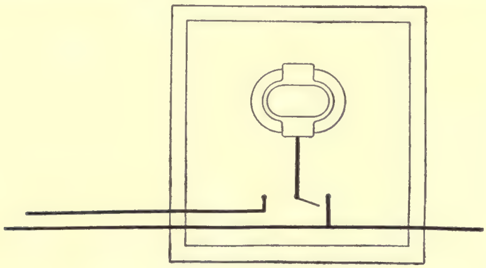


Fig. 163. Throw-Over for Transformer.

be used, although they are preferred in some cases where switching under load may be necessary at times.

Types of disconnectives which utilize an air break are therefore quite commonly used for emergency disconnectives.

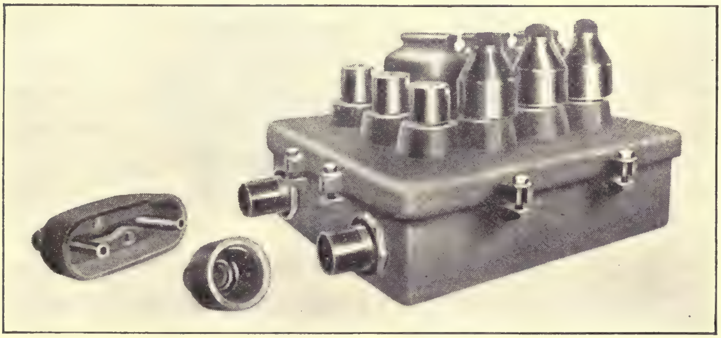


Fig. 164. Multiple-conductor Selector Switching Box.

Fig. 164 illustrates a switching box in which multiple-conductor cables are terminated under compound in the box, with the individual conductors brought to the lower end of porcelain tubes in which contacts are carried.

The terminals of each circuit are brought to the outer row

of tubes and the transformer is connected to the middle row. When the source of energy is to be transferred, the cap is lifted and placed in the opposite position. This type of box is also a convenient means of making emergency connections to the mains of an adjacent circuit where the connection is normally open. In such cases one row of tubes is left dead and the caps are left on the dead side normally. The tubes of the unused side are protected from moisture and dirt by a dummy cap set over them.

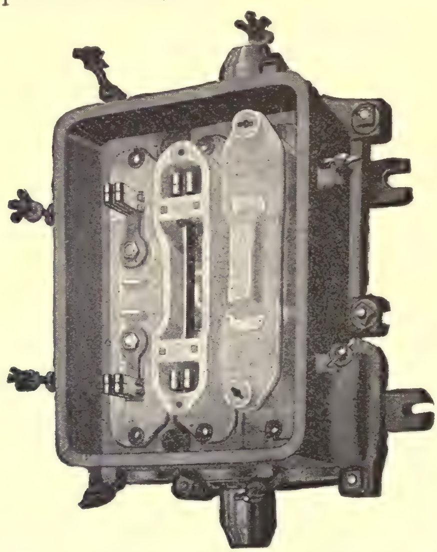


Fig. 165. High-tension Disconnective Box.

In other types of primary junction box the disconnector is a knife-blade switch which can be removed after opening if desirable. This blade is handled by a rod and hook which makes it safe to handle the knife blade. In other types, the knife blade is arranged to be withdrawn or inserted by attachment to a porcelain handle as shown in Fig. 165. This arrangement is also used for primary fuses and obviates the necessity for the use of the hook and rod.

CHAPTER XIII.

DISTRIBUTION ECONOMICS.

There are various problems involved in the engineering design of a distribution system which have an economic aspect in that they have a direct relation to the success of the property as a business enterprise. Distributing feeders form a considerable part of the plant investment and their design affects the generating plant and the efficiency of operation.

The distributing voltage being fixed by practical considerations of safety and continuity of service, it is the usual practice in large systems to adopt one or two standard feeder capacities which are made as large as is practical. With transmission lines, when a standard voltage has been established, it is usual to adopt certain line capacities beyond which it is not desirable to go. Thus the problem usually resolves itself into the selection of the proper size of conductor for the unit of load adopted.

Economical Size of Conductor. — The determination of the most economical sizes of conductors for feeders, mains and transmission lines is of great importance, since the distributing equipment forms a large proportion of the investment and net earnings are affected by its design to a large extent.

In the selection of the size of a conductor for a feeder or transmission line the energy loss tends to diminish as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss also decreases as the size of the conductor is increased.

Hence there is a point at which the sum of the fixed charges

on conductor, fixed charges on generating capacity, and the value of energy loss is a minimum. The size of the conductor with which this condition of minimum annual cost is realized is that which it is the most economical to employ.

The fixed charges are composed of interest on the capital, depreciation of the physical property, taxes and insurance.

The energy loss is computed at the cost of energy as delivered at the switch-board from which the circuit is supplied.

In calculating interest the investment figure should include the cost of the conductor with its insulation and any other expense which is proportional to its cross-section.

Interest should be figured at the current rates for the use of money for public service utilities.

Depreciation. — Depreciation should be based upon the working life of the apparatus and conductors, allowing for the possibility of changes in the state of the art, and the probable second-hand value of the equipment at the end of its period of service.

The rate of depreciation is stated as a percentage and varies with the different kinds of equipment. For instance, if the working life of a lead cable is found by experience to be ten years, the depreciation would be ten per cent annually, less the junk value of the copper and lead at the end of the ten-year period. If the junk value were 50 per cent of the original cost of the cable, the depreciation would be 5 per cent, or if the junk value were 25 per cent, the depreciation would be $\frac{1}{10}$ of 75 per cent, or 7.5 per cent annually.

Weatherproof wire consists of about 80 per cent copper and 20 per cent insulation in the sizes ordinarily used for feeders. There is no depreciation of the copper except the labor of replacing it at intervals of ten to fifteen years when the insulation is worn out. The increase in the value of copper with advancing years tends to offset the loss on the insulation,

so that at best it is an uncertain quantity. It is conservative, however, to figure 10 per cent on the 20 per cent of insulation or 2 per cent and 1 per cent for the labor of replacing, making a total of 3 per cent of the original cost of the wire.

The life of lead-sheathed paper or rubber cables is as yet indeterminate, but there is good reason to believe that these may be serviceable for 15 to 20 years. The junk value is comparatively high, as the copper is a large part of the original cost, and the lead sheath constitutes a considerable percentage of the cross-section of the cable. It is therefore fair to estimate the depreciation on lead-sheathed cables at 3 per cent for cables of 4/0 and larger and at 5 per cent for the smaller sizes.

In a growing system the replacement of cables due to the expansion of the load results in more rapid depreciation than is experienced in a system where the feeder conductors remain undisturbed until they are too far gone to be of further service.

The rate of figuring depreciation is necessarily a matter of judgment based on the best experience available and is therefore apt to vary somewhat according to the circumstances.

The continued evolution of the art of manufacturing electrical apparatus and the rapid growth of the central station industry have caused the abandonment of the older types of machinery long before they were worn out, in order to effect the savings in operation with the more efficient newer types. This has resulted in higher rates of depreciation than would have prevailed had the machinery been able to serve out its normal life. This form of depreciation is called obsolescence, and is an important factor in rapidly growing systems.

Where the prime mover is a water wheel the life of the unit as a whole is more likely to be realized in actual service, as the possibilities of improvement in hydraulic equipment are more limited than with steam machinery, and the size of the unit

is usually made as large at the start as the water supply will justify.

Managers of large properties who have carried their equipment through the evolution of the art with a rapid growth are therefore apt to consider depreciation at a higher rate than those who are starting with new and modern equipments. The more experienced figure depreciation on generating equipment at about 6 to 7 per cent and on buildings at 3 per cent, with an average of about 5 per cent on the whole plant.

It is assumed in the above figures that the repair and renewal account will stand from year to year all necessary maintenance costs which are required to keep the plant in economical operating condition and not allow the property to run down.

The rate on a hydraulic development might be considered somewhat lower because of the more stable character of the equipment and the smaller proportion of the total investment which is subject to wear and tear. The damage from floods must be reckoned with, however, and this sometimes reduces the life of the investment very greatly.

General Equation for Minimum Annual Cost. — The total annual cost of an electric circuit may be expressed by a general equation as follows:

$$Y = \frac{a}{R} + bC^2R + cC^2R.$$

In this expression $\frac{a}{R}$ represents the fixed charges on the conductors and their insulation, if any, a being a constant which may be determined for bare, weatherproof or lead covered conductors with sufficient accuracy for this purpose. This portion of the cost is proportional to the conductivity, $\frac{1}{R}$, of

the conductor. bC^2R represents the fixed charges on the generating station capacity required to supply the C^2R loss, b being a constant which is fixed by the type of generating plant involved. cC^2R is the value of the energy loss on the circuit per annum, in which c is a constant depending upon the unit cost of producing energy and the character of the load carried by the circuit.

In each of these three elements of cost R is the resistance per 1000 ft. of the conductors of the circuit.

The value of Y, the total annual cost, is a minimum by the rule of calculus when $\frac{dy}{dR} = 0$.

$$\frac{dy}{dR} = \frac{(b + c)\, C^2R^2 - a}{R^2}.$$

When $\frac{dy}{dR} = 0$, $(b + c)\, C^2R^2 - a = 0$ and $C^2R^2 = \frac{a}{b + c}$,

$$CR = \sqrt{\frac{a}{b + c}},$$

from which it is known what value of R and hence what size of conductor is most economical for any known value of C, the current carried by the circuit at the time of maximum load of the year.

It being customary in distribution engineering to adopt a unit feeder load as standard, the proper size of conductor to use as a standard feeder may be determined by this formula. Or, if a standard size of feeder conductor is adopted, the most economical maximum load for the standard feeder may be found.

It is assumed that the voltage has been established and the formula is therefore applicable to conditions already existing. The length of the feeder and the working voltage are not factors in the problem since the economic balance is de-

termined solely by the values of C and R for a given set of working conditions.

Fixed Charges on Conductors. — The value of the conductors composing a circuit is directly proportional to their size and inversely to their resistance when the conductors are bare or insulated for overhead construction. With lead-sheathed cable the cost is nearly proportional, when a few adjacent sizes are considered in comparison with each other.

For bare wire the product of weight per 1000 feet W by resistance per 1000 feet for all sizes is $WR = 32$, while with weatherproof insulation it is $WR = 38$ for the sizes No. 4 to No. 0, or 36 for sizes from 2/0 to 350,000 c.m. The value of 1000 feet of conductor at 15 cents per pound is therefore .15 W dollars. Hence, when $W = \frac{38}{R}$, the cost per conductor per thousand feet is $\frac{.15 \times 38}{R}$ dollars.

With fixed charges at 9 per cent this element of annual cost is $\frac{a}{R} = \frac{.09 \times .15 \times 38}{R} = \frac{.513\ L}{R}$ dollars per year per conductor. With underground conductors the value of insulation and lead sheath is a large proportion of the cost of the smaller sizes of cable, and a change in the size of the copper conductor does not make a proportionate change in the cost of the cable.

The resistance per 1000 c.m. per 1000 feet of copper at ordinary temperatures is about 10.4 ohms. If R is resistance per 1000 feet and M is the number of thousands of circular mils, the cost of a single-conductor cable is M times the cost per 1000 circular mils. $M = \frac{10.4}{R}$ and the cost of the cable is $\frac{10.4 \times P}{R}$, where P is the cost per 1000 circular mils and per thousand feet.

Table XII gives the cost per 1000 circular mils of various sizes of single- and three-conductor lead-sheathed cables for low-tension work and for ordinary primary distributing voltages.

TABLE XII.—COST OF LEAD-SHEATHED CABLES.

Size conductor.	Cost per 1000 c.m. per 1000 feet.			
	Single cond. 3000 volts.	Three cond. 10,000 volts.	Single cond. 300 volts.	Three cond. 300 volts.
4	$2.80	$2.60	$2.40	$2.05
2	2.20	2.05	1.95	1.85
0	1.90	1.75	1.70	1.60
00	1.65	1.55	1.60	1.50
000	1.50	1.45	1.45	1.40
0000	1.40	1.35	1.35	1.30
250,000	1.30	1.25	1.30	1.25
350,000	1.20	....	1.15	....
500,000	....	....	1.00	....
750,000	....	....	.90	....
1,000,000	....	....	.80	....

For single-conductor low-tension cable the value of P in Table XII averages $1.20 for cables from 2/0 to 500,000 c.m. and the value of each conductor is $\frac{10.4 \times 1.2}{R} = \frac{12.48}{R}$ per 1000 feet. With fixed charges assumed at 9 per cent, the annual conductor cost per 1000 feet is $\frac{a}{R} = \frac{.09 \times 12.48}{R} = \frac{1.12}{R}$ per conductor. In applying this, if the most economical size proves to be below or above the sizes for which the cost was assumed, the figure should be corrected, using the price per 1000 c.m. corresponding to the size which seems on the first approximation to be the most economical. In this way the most economical size may be determined on the second determination if the first seems to have been based on false premises.

With three-conductor cables the cost per 1000 circular mils in Table XII is based on the total cross-section of the three

conductors. In this case the cost of the cable is $\frac{3 \times 10.4\,P}{R}$ and $\frac{a}{R} = \frac{0.09 \times 3 \times 10.4\,P}{R} = \frac{2.8\,P}{R}$.

Thus the value of *a* may be derived for different kinds of cable and at various values of copper, lead and insulation. It must be borne in mind that these values are for a single cable. Where a circuit is composed of more than one cable, this must be taken into account in figuring the total annual cost for the circuit. That is, for a two-wire circuit the value of *a* is doubled and for three cables it is tripled.

Fixed Charges on Generating Equipment. — In estimating the value of generating capacity required to deliver the loss at maximum load, the cost of boilers, prime movers and generators should be included, as all are affected. This cost varies greatly in different plants, depending upon the size and character of the equipment. In engine-driven stations of less than 1000 kw. the value of this equipment runs from \$125 to \$150 per kilowatt, while in turbine plants this cost is reduced to \$90 or \$100 per kilowatt. In turbine plants of 10,000 kw. and upward the investment exclusive of buildings and real estate is as low as \$70 in some cases.

Where conditions are such that generator capacity could be released for commercial load by the use of larger conductors, the fixed charges on generating equipment should be considered one of the elements of annual cost of operating a circuit. This is usually the case where alternating current is distributed through potential regulators or through substation transforming apparatus, which converts the feeder loss into a load on the armature of the generator.

Where the loss is represented by the range of voltage of the generator fields, a saving in generating capacity cannot always be realized, as operating conditions usually necessitate a range

of 10 to 15 per cent in the generator fields, which proportionately reduces the ampere rating of the armature for a given rated capacity.

The station capacity required to supply the energy loss at the time of the annual maximum load is $\frac{C^2R}{1000}$ kw. per 1000 feet of conductor.

The value of station capacity required to supply the loss on a feeder when the cost is \$100 per kilowatt is $\frac{100 \times C^2R}{1000}$ and the fixed charges at 12 per cent are $bR = .12 \times .1\ C^2R = .012\ C^2R$ dollars per conductor.

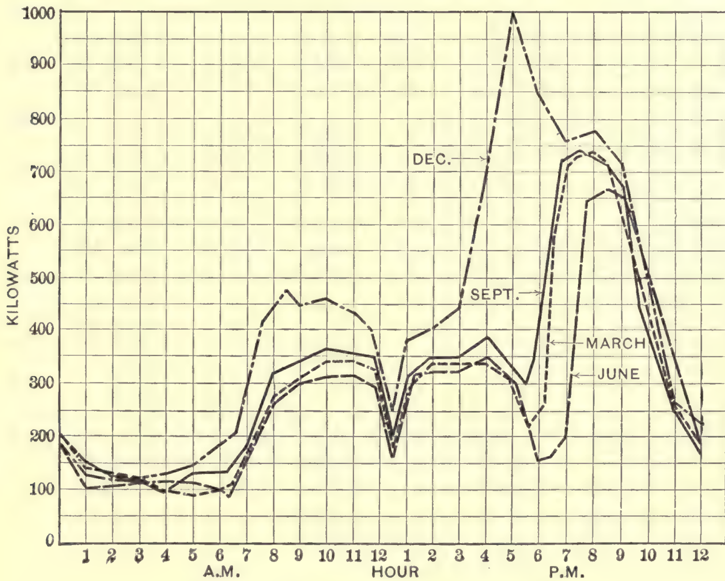


Fig. 166. Lighting Load Diagrams.

Energy Loss. — The loss of energy on a circuit during a year is dependent upon the variation of load from hour to hour and from day to day throughout the year.

The variation from hour to hour in general distribution

work changes from day to day, depending upon the habits of the people who use the electricity and from season to season as the length of the daylight hours changes. During the winter months the use of light begins in the late afternoon before the day power load has been cut off. This overlapping causes a very sharp peak in the load curve in many cases. In Fig. 166 typical average curves are shown for a lighting

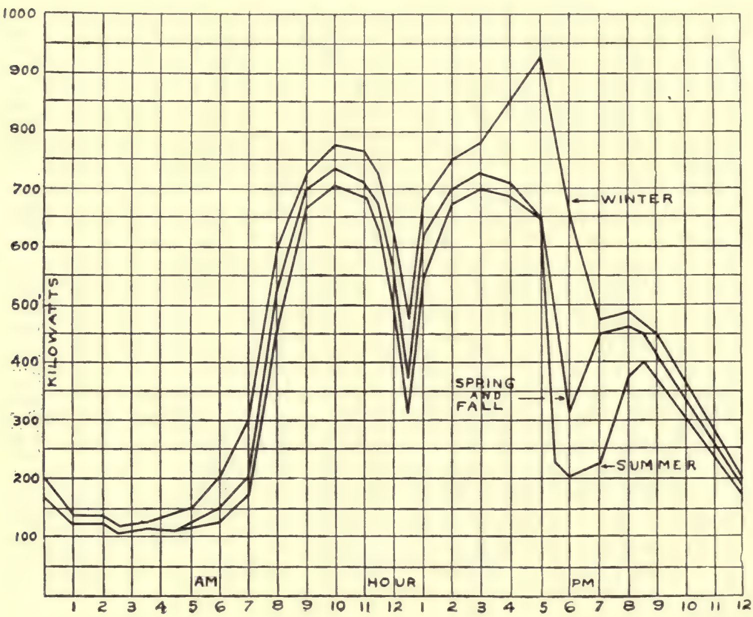


Fig. 167. Power Load Diagrams.

feeder which carries some day power load, for the months of March, June, September and December. The energy loss will evidently be different on this feeder each month in the year, being least during the summer months and most during December. Fig. 167 shows similar curves for power circuit which carries some lighting during the evenings. This curve is also similar to that which prevails on a transmission system

where a considerable amount of power is supplied to industrial concerns during the day.

The annual loss on a circuit carrying load of given characteristics may be computed with sufficient accuracy for practical purposes as follows:

Taking a curve representing the load in amperes on an average day in March, assume a resistance of one ohm and compute the value of C^2R for each hour of the day. The sum of these 24 quantities divided by 1000 is proportional to the loss in kilowatt hours on an average day in March. Repeat this operation for the June, September and December curves. Add the sum of the four curves and multiply by 91, this being the number of days in each quarter of the year. This grand total is proportional to the annual loss in kilowatt hours on any feeder carrying a load having the general characteristics assumed.

In cases where power is generated by water fall, the energy loss on the feeder may be neglected. The power absorbed by the line at the time of maximum load must be considered, however, in case it has a marketable value when the plant is fully loaded.

Loss Factor. — The ratio of the loss as thus calculated to the value of the loss if the feeder had carried the maximum load of the year every hour of the year may be called the *loss factor*, just as the ratio of the actual output for the year to the possible output at the rate of the maximum load is called the *load factor* of a circuit.

For instance, if a circuit carries a maximum load of 100 kw. and delivers an amount of energy equivalent to a load of 100 kw. during 2190 hours per year, the load factor of the feeder for the year is $\frac{2190}{24 \times 365} = 25$ per cent.

Similarly if the total energy *loss* on a circuit for a year is

equivalent to the loss at maximum load multiplied by 2190, the loss factor for the feeder year is 25 per cent.

If C is the current at the annual maximum load and R is the resistance per 1000 feet of conductor, the loss at the time of the annual maximum load is C^2R.

If the loss factor of the feeder is 20 per cent, the annual loss is

$$\frac{C^2R \times .2 \times 365 \times 24}{1000} = 1.752\, C^2R.$$

The loss factor for a load having the characteristics illustrated in Fig. 166 is 16 per cent, while that of the curves in Fig. 167 is 28 per cent.

In a constant-current circuit the loss factor is the ratio of the number of hours the circuit is operated during the year to the total number of hours in the year. It is usually the same as the load factor of the circuit.

Calculation of Loss. — With the character of the load curve known, the loss factor may be determined in the manner described and the annual loss of energy calculated in terms of R, the resistance per 1000 feet of conductor.

The loss at the time of the annual maximum load being C^2R, the annual loss in kilowatt hours is equivalent to the product of the maximum load loss by the number of hours in the year and by the loss factor, F.

There being 8760 hours in a year, this is $\frac{C^2R \times 8760 \times F}{1000}$ kilowatt hours. The loss $= 1.4\, C^2R$ when the loss factor is 16 per cent. The value of this energy may be computed at the cost of fuel and supplies, as no extra labor is required to deliver it, as a rule. The cost can therefore be taken at about 1 cent in smaller plants, .70 cent in larger engine plants and .5 cent to .4 cent in turbine plants.

At 1 cent per kilowatt hour the value of the energy loss per

conductor is $C^2R = .014\,C^2R$ dollar per year at 16 per cent loss factor, or $.0245\,C^2R$ at 28 per cent loss factor.

Summary of Annual Costs. — The total annual cost is therefore the sum of the three quantities $\frac{a}{R}$, bC^2R and cC^2R. For weatherproof wire with station capacity at \$100 per kilowatt, a loss factor of 16 per cent and energy at 1 cent a kilowatt hour, the annual cost per 1000 feet of circuit is

$$\frac{a}{R} + bC^2R + cC^2R = \frac{.513}{R} + .012\,C^2R + .014\,C^2R$$

$$= \frac{.513\,L}{R} + .026\,C^2RL.$$

It is desired to ascertain when the value of these three elements will be a minimum for given values of C, the current at the time of the annual maximum load. When $\frac{dy}{dR}$ is 0,

$C^2R^2 = \frac{a}{b+c}$ and $C^2R^2 = \frac{.513}{.026} = 19.7$, whence $CR = \sqrt{19.7}$ $= 4.44$ and $R = \frac{4.44}{C}$ when the most economical size is used. For instance, if $C = 100$ amperes, $R = .0444$ ohm, which is about the resistance per 1000 feet of 4/0 cable.

This applies only to a two-wire or three-wire circuit in which each conductor carries current normally. With a three-wire Edison feeder with neutral half the size of the outers the amount of copper is increased 25 per cent, without increase in b and c, and $\frac{a}{R} = \frac{.513 \times 1.25\,L}{R} = \frac{.641\,L}{R}$. Hence $CR = \sqrt{\frac{.641}{.255}}$ $= 5.01$ for the outer conductors of a three-wire circuit.

Similarly with a four-wire three-phase feeder with neutral the same size as the phase wires the amount of copper is

increased 33 per cent and $\frac{a}{R} = \frac{.513 \times 1.33}{R} = \frac{.684}{R}$, whence

$CR = \sqrt{\frac{.684}{.0255}} = 5.17.$

These values involve a current density of about .5 ampere per 1000 circular mils, which is much lower than is commonly found. This is due perhaps to the fact that the expenditure of funds for line conductors is plainly evident, while the value of the generating capacity which is tied up by cutting the size of the conductor to a minimum is not so apparent. Where there is reserve generating capacity, which can as well be used to supply line losses as not, the annual cost for the conditions assumed for a two-wire feeder is

$$\frac{a}{R} + cC^2R = \frac{.513}{R} + .0105\,C^2R.$$

Hence $CR = \sqrt{\frac{.513}{.0105}} = 7.0$ for a circuit in which each wire carries current,

$CR = \sqrt{\frac{.641}{.0105}} = 7.81$ for a 3-wire Edison feeder with neutral half size,

or $CR = \sqrt{\frac{.684}{.0105}} = 8.07$ for a 4-wire 3-phase feeder neutral same size.

With 100 amperes $R = .07$ which is approximately the resistance of 2/0 conductor.

Practical Illustrations. — For illustration, a few cases which are common in practice for both larger and smaller systems are carried through herewith.

Case I. — Weatherproof wire at 15 cents a pound, generating capacity at \$80 a kilowatt, energy .5 cent per kilowatt

hour, and load curve such that the loss factor is 18 per cent. Under these conditions

$$\frac{a}{R} = \frac{38 \times .15 \times .09}{R} = \frac{.513\ L}{R}, \quad bC^2R = \frac{80 \times .12}{1000}\ C^2R = .0096\ C^2R,$$

$$cC^2R = \frac{.005 \times 8760 \times .18\ C^2R}{1000} = .0079\ C^2R.$$

Hence $CR = \sqrt{\frac{.513}{.0175}} = 5.43$ per conductor which carries a current C.

If generating capacity is ignored, $CR = \sqrt{\frac{.513}{.0079}} = 8.1$. This calls for a conductor having .081 ohm resistance for 100 amperes, which is about equivalent to 1260 circular mils per ampere. For three-wire Edison circuits $CR = 9.0$ and for four-wire three-phase circuits $CR = 9.3$.

Case II. Underground cables at values given in Table XI, generating capacity at $80 per kilowatt, energy at .4 cent per kilowatt hour, and loss factor at 25 per cent. With single-conductor low-tension cable, No. 2 to 2/0, the cost per 1000 c.m. averages $1.80.

Hence $$\frac{a}{R} = \frac{.09 \times 10.4 \times 1.8}{R} = \frac{1.68}{R},$$

$$bC^2R = \frac{80 \times .12\ C^2R}{1000} = .0096\ C^2R,$$

$$cC^2R = \frac{.004 \times 8760 \times .25\ C^2R}{1000} = .0087\ CR^2,$$

and $$CR = \sqrt{\frac{.168}{.0183}} = 9.5 \text{ per conductor.}$$

With 100 amperes $R = \frac{9.5}{100} = .095$, which is about the resistance of No. 0 conductor.

If the current were 500 amperes, the value of cable should be chosen for about 750,000 c.m., which is \$.90. Then

$$\frac{a}{R} = \frac{1.68 \times .90}{1.8\,R} = \frac{.84}{R}, \qquad CR = \sqrt{\frac{.84}{.0183}} = 6.7.$$

At 500 amperes R should be made $\frac{6.7}{500} = .0134$, which is approximately the resistance of a 750,000 c.m. cable.

If this were a low-tension feeder with neutral half size the cost of the feeder would be \$1.80 + \$1.30 = \$3.10 per 1000 c.m. Hence

$$\frac{a}{R} = \frac{3.10 \times .10 \times 10.4}{R} = \frac{3.00}{R}, \qquad bC^2R = 2 \times .0096\,C^2R = .0192\,C^2R$$

and $cC^2R = 2 \times .0087\,C^2R = .0174\,C^2R$ for the feeder.

$$CR = \sqrt{\frac{3.00}{.0366}} = 9.0 \text{ and } R = \frac{9.0}{500} = .018,$$

which is between the resistance of 500,000 and 600,000 c.m. cable. This is for the outer wires only, the neutral being considered as carrying no load and as half the size of the outer.

In the case of a four-wire three-phase feeder with neutral the same size as the phases, the value of the feeder at 100 amperes is $4 \times 1.90 = \$7.60$ and $\frac{a}{R} = \frac{7.11}{R}$.

$$C^2R\,(b + c) = 3 \times .0183\,C^2R = .0549\,C^2R.$$

Hence $$CR = \sqrt{\frac{7.11}{.0549}} = 11, \qquad R = \frac{.11}{100} = .011,$$

which is nearest the resistance of No. 0 cable.

Case III. Three-conductor cables, generating capacity at \$80 per kilowatt, energy at .4 cent per kilowatt hour and loss

factor at 25 per cent, 10,000 volts three phase, 100 amperes. The cost of cable is \$1.75 per thousand circular mils.

$$\frac{a}{R} = \frac{\$1.75 \times .09 \times 10.4}{R} = \frac{1.64}{R} \text{ per conductor,}$$

$$C^2R\,(b + c) = .0183\, C^2R \text{ per conductor,}$$

$$CR = \sqrt{\frac{1.64}{.0183}} = 9.4, \qquad R = \frac{9.4}{100} = .094,$$

which is nearest the resistance of 0 cable.

Case IV. Bare wire overhead, water power generating capacity at \$150 per kilowatt, copper at 15 cents per pound, current 150 amperes. The depreciation item in the fixed charges on conductors may be ignored, as there is no insulation to be replaced. Fixed charges may therefore be computed at 5 per cent interest and 1 per cent taxes, or 6 per cent on the line wire.

$$W = \frac{32}{R} \text{ and the cost per 1000 feet is } .15\, W = \frac{.15 \times 32}{R}.$$

Hence
$$\frac{a}{R} = \frac{.06 \times .15 \times 32}{R} = \frac{.288}{R}.$$

The value of station capacity at \$150 per kilowatt is

$$\frac{150\, C^2R}{1000} = .15\, C^2R \text{ and } bC^2R = .15 \times .12\, C^2R = .018\, C^2R.$$

The power being derived from water $c = 0$. The annual cost is

$$\frac{a}{R} + bC^2R = \frac{.288}{R} + .018\, C^2R. \qquad CR = \sqrt{\frac{.288}{.018}} = 4.$$

At 150 amperes $R = \frac{4}{150} = .0266$, which is about the resistance of a 350,000 c.m. cable.

This represents a very low current density, due to the fact that fixed charges on line capacity are less than half those on

station capacity. It is therefore economical to invest money in line conductors which will make more of the generating capacity available for commercial load under these conditions.

Case V. Constant-current system, direct current, 7 amperes, weatherproof wire, generating capacity $200 per kilowatt, cost of energy 1 cent per kilowatt hour, operated dusk to daylight every day, making the loss factor 50 per cent.

As in Case I, $a = \frac{.513}{R}$ for weatherproof wire. The cost of generating machinery for this class of service is usually very high. Where direct current is used the units must be small and the cost per kilowatt high, as the generators themselves cost more on account of the high voltage and the arrangement for driving, whether by motors or shafting, is necessarily expensive. Where the shafting is dispensed with and the generators are driven by alternating-current motors, the investment per kilowatt is very high, as the capacity of alternating-current generator, alternating motor and constant-current generator must be included in figuring the cost per kilowatt of capacity. At $200 per kilowatt,

$$bC^2R = \frac{200 \times .12}{1000} C^2R = .024\, C^2R.$$

With energy at 1 cent per kilowatt hour and the loss factor at 50 per cent $c = \frac{.01 \times 8760 \times .5}{1000} C^2R = .043\, C^2R.$ The total is therefore $\frac{.513}{R} + .067\, C^2R.$ Whence $CR = \sqrt{\frac{.513}{.067}} = 2.8.$ At 7 amperes $R = .4$ ohm, which is nearly the resistance of No. 6 B. & S.

In cases where distributing feeders are supplied through a transformer substation, the calculation for the best size of feeders should be made with the cost of generating, transmission and substation equipment in view, in determining the fixed charges on generating capacity.

The curves in Fig. 168 show how the line charges, station capacity charges and line losses (with steam power) are related to each other where the line current is 100 amperes. The line is weatherproof wire, and other conditions are those assumed in Case I.

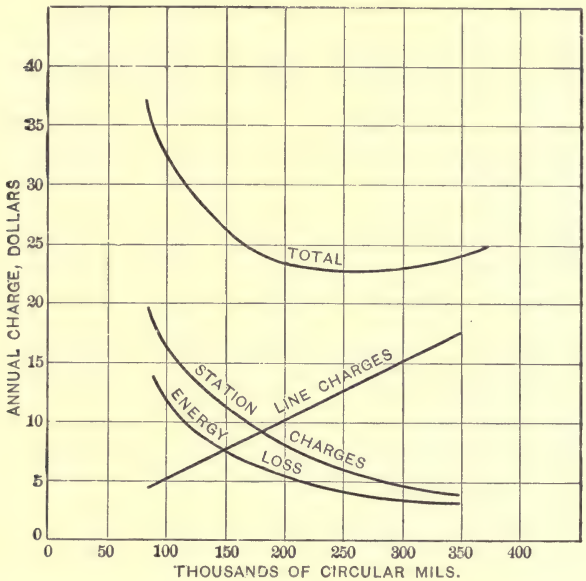


Fig. 168. Elements of Annual Cost of Overhead Circuit.

The application of the foregoing principles to distributing mains cannot be carried out, as such mains carry indeterminate loads and should be so designed that the drop on them will not exceed 2 per cent. In many cases this requirement involves the use of larger conductors than would be required from mere economic considerations of line loss. In other words the economic limit in this part of the system is the life and performance of incandescent lamps and these often far outweigh line losses in mains.

In alternating-current systems the selection of transformers

and their location with reference to the secondary mains involves economic considerations which are very complex and do not admit as simple a solution as is possible with feeders and transmission lines. This subject is fully discussed in the chapter on Secondary Distribution.

Diversity Factor. — In the distribution of electricity for general lighting and power purposes, the maximum demands of consumers are made at different hours of the day, and vary from day to day during the week and from month to month during the year. The maximum demands of lighting consumers are affected by the changing seasons, by the character of the population served, and by the nature of the premises in which the lighting is used.

The residence consumer varies his demands according to the size and character of his dwelling place, having his house well lighted at times and almost totally dark on other evenings. Perhaps his neighbors are well lighted up on the evenings when he is not home. Thus the maximum demands of individual consumers come on different days or at different hours of the day so that their sum is much greater than the highest demand made upon the distributing system at one time.

With store and other commercial lighting, the demands of the individual users are apt to be more uniform, since the conditions under which lighting must be used are fixed by practical necessity and by customs which the user is not at liberty to ignore. The proprietor of the store must burn his window lights in order to compete with his neighbors, and the owner of the factory must furnish his employees sufficient light to to enable them to work to advantage. The diversity factor between such consumers is therefore smaller than it is between residence consumers.

The demand for electricity for power purposes is greatest during the hours when the lighting load is smallest. The

combined effect of these influences is to produce a smaller maximum demand at the point of supply than would be required if these demands were coincident. The sum of the maximum demands of individual consumers is greater than that on the distributing mains from which they are supplied. The sum of the maxima on distributing mains is greater than that of the feeder, the sum of the feeder maxima is greater than that at the substations, and the sum of the substation maxima is more than the coincident maximum of the generating station.

The quantitative expression of this relation between the individual demands of the members of a group of users of electricity to the maximum simultaneous demand at the point of supply is called the Diversity Factor of the group, or the Group Diversity Factor.

The definition of the Diversity Factor of a group has been stated in the following form:

"Group Diversity Factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system, to the maximum demand of the whole system or part of the system under consideration, measured at the point of supply."

For illustration, if the sum of the individual demands of a group of 50 residence consumers is 30 kw. and the maximum demand made by this group upon the transformer which supplies them is 10 kw., the Diversity Factor of the group is $\frac{30}{10} = 3$.

Or if the sum of the maxima of a group of feeders supplying a district is 2300 kw. and the maximum demand upon the substation which supplies them is 2000 kw., the group diversity factor of these feeders is $\frac{2300}{2000} = 1.15$.

Similarly one may derive group diversity factors for the

transformers supplying a district, or for a group of substations or towns making up a large system.

Nature of Diversity. — The existence of a diversity factor is thus due to the differences in the maximum demands of different consumers as to the hour of the day and as to the days of the season, or year. The former may be termed daily diversity and the latter, seasonal or yearly diversity.

Daily diversity is that which arises from the fact that different consumers make their heaviest demands at various

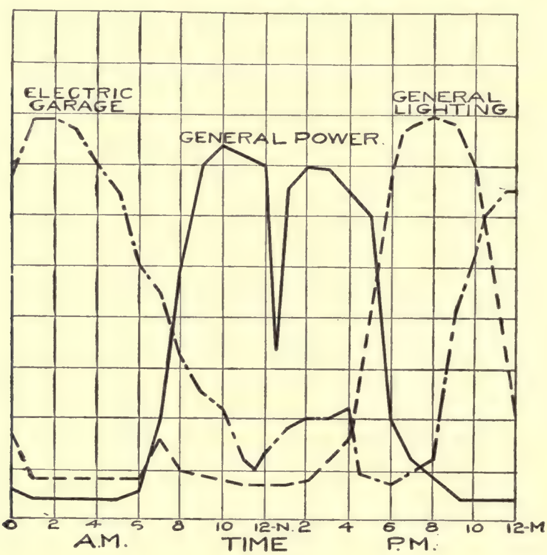


Fig. 169.

hours of the same day. This is illustrated by the load diagrams of Fig. 169 which shows the daily diversity between power users, lighting consumers and electric garages.

Seasonal diversity, or yearly diversity, is that which is due to the fact that different consumers make their maximum demands on different days of the season, or year, respectively.

Weekly and monthly diversity factors may also be required for special purposes, at times.

Familiar examples of seasonal diversity are found in the manufacture of ice, amusement parks, irrigation pumping etc. Weekly diversity is exemplified in the heavy lighting loads that occur on Saturdays in certain places, while the maximum use of power and lighting in industrial establishments occurs on other days of the week and is below normal on Saturdays. A considerable part of the diversity of residence consumers is seasonal or monthly rather than daily. There are always certain ones of a group of residence users who are away from home for an evening and whose requirements are therefore below normal. On the other hand, every member of the group is likely to have his home open to guests on certain evenings of the year when he uses more than his average requirements. Thus the sum of the maxima of the members of the group is much higher than the coincident demand at the transformer and we have seasonal diversity among residence consumers.

The determination of diversity factors must therefore be based upon records of maxima for the months of the year as well as upon load diagrams for the day on which the maximum coincident demand of the year occurred.

The diversity factor, as defined by the standard definition, may apply to a group of consumers in a given locality served by a single transformer, to the feeders supplied by a single substation or to a group of towns supplied by a transmission system. It may also be applied to a group of classes such as general power, commercial lighting, residence lighting, and others whose hours of use are known. It implies the existence of a group, and is therefore a group diversity factor. Its effect is to produce a coincident demand upon the source of supply which is less than the sum of the separate demands. It reveals nothing, however, as to how much any

individual user or group of users contributes to the reduction in demand.

For certain purposes it is necessary to know how much each individual of a group contributes to the group diversity. Electric garages, ice manufacturers, water pumping plants and others which have very high diversity when taken in comparison with the general system load diagram, require special consideration and a further definition of diversity factor. This may be termed the individual diversity factor and is defined as follows:

"Individual diversity factor is the ratio of the maximum power demand made by any subdivision of a system, to the coincident demand made by such subdivision at the hour of the maximum load upon the source of supply."

If, for instance, a class of consumers, such as ice manufacturers, makes a demand of 2000 kilowatts during the summer months, and a demand of 200 kilowatts at the hour of the annual maximum in the winter months, the individual diversity factor of ice manufacturers as a class is $\frac{2000}{200} = 10$.

A clear conception of the relation of the group diversity factor of a group to the individual diversity factor of a member of the group is quite essential in determining the investment portion of the cost of serving any class or community of consumers.

Illustration. — For example, take a purely residence suburb which is a part of a district supply system from which commercial lighting, industrial power and other classes of service are supplied in other localities. In this residence suburb, the group diversity factor will be about 3.5, that is, the sum of individual consumers' demands will be about 350 kilowatts for each 100 kilowatts of demand at the substation supplying this suburb.

However, the individual diversity factors of the various consumers in this suburb may range from 1 to 10 or more. The resident who happens to have his house open for a social event and is using his annual maximum demand at the hour of the annual substation maximum has an individual diversity factor of 1. The resident whose house is empty at that hour, with perhaps one 50-watt lamp burning, has an individual diversity factor of 10 or more. The weighted average of the individual diversity factors of all the consumers is the group diversity factor.

The load of the residence suburb, considered now as a wholesale user from the transmission system, is combined with the loads of other towns, which affects the total demand upon the transmission system and power station. There may be a coincident demand of 20,000 kilowatts on the power station, with demands at various times on the substations aggregating 30,000 kilowatts. The group diversity factor of all the substations is 1.5. The individual diversity factor of the residence suburb may be anything from 1 to 5 or more. If the annual system maximum occurs on Christmas Eve, the residence suburb will probably have an individual diversity factor of very nearly 1, but if the annual system maximum occurs during daylight hours, the individual diversity factor of the residence suburb may be 10 or more. These conditions are illustrated by the load diagrams in Fig. 170, in which curve *C* is the load diagram for the residence suburb for December 20th, the day of the general system maximum, *D* is the curve for the day on which the annual maximum of the substation occurred, and *A* and *B* are typical system load diagrams for systems in which the day power and evening lighting loads respectively predominate. If the residence substation is a part of a system with the load diagram *A*, the individual diversity factor of this substation maximum of 450 kilowatts

to the substation load of 90 kilowatts at 10 A.M., the hour of the system maximum, is $\frac{450}{90} = 5$.

If this substation is a part of a system such as that represented by load diagram *B*, the individual diversity factor of the substation at 5.30 P.M., on December 20th, the day of the general system maximum, is $\frac{450}{350} = 1.28$.

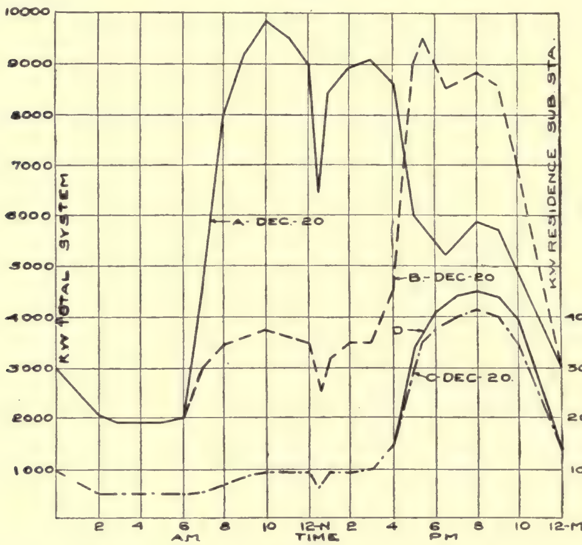


Fig. 170.

Group Diversity Factors of Consumers. — An analysis of diversity factors for various classes of consumers in the city of Chicago has been made by the authors, based upon observations made at various points in the alternating-current distributing system.

The observations were taken at the consumers' meters, at the line transformers, at the substation switchboard and at the generating station. The relation of these various points is illustrated diagrammatically in Fig. 171.

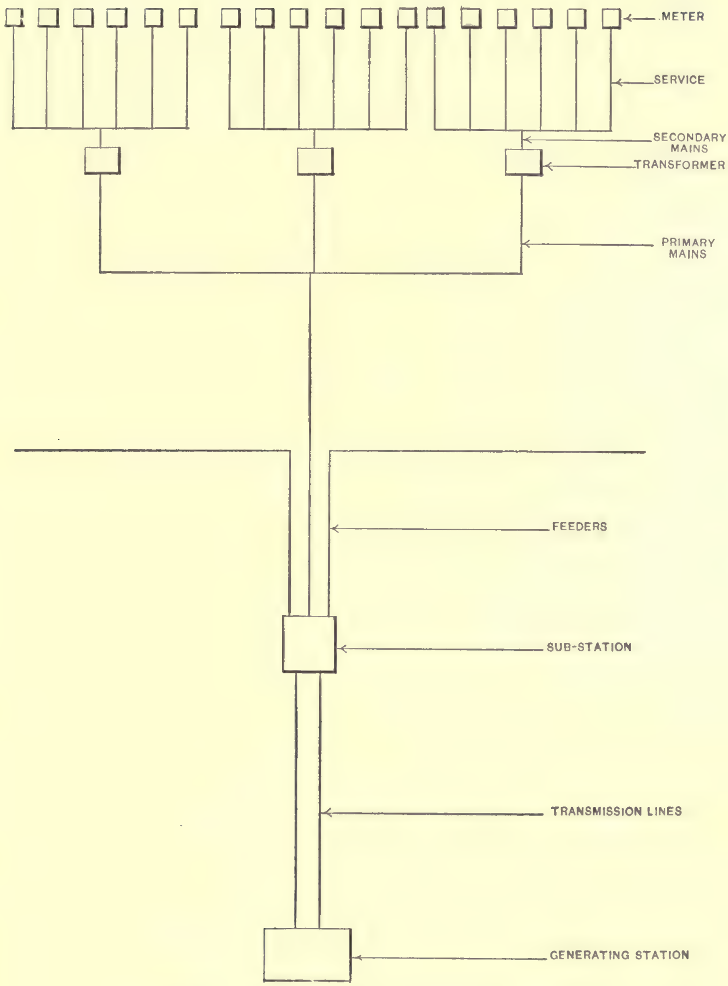


Fig. 171. Elements of a Distribution System.

Consumers of electricity were classified as residence light, commercial light, general power and large users. The commercial light includes the average small and medium-sized stores and shops whose maximum demand is under 50 kw.; general power includes all miscellaneous power users having less than 50 kw.; while large users are the light and power consumers having 100 to 500 kw.

TABLE XIII.

RESIDENCE LIGHTING.

Group.	No. of cons.	K.W. conn. per cons.	Sum of cons. max.	Max. of group.	Diversity factor.	Aver. cons. load factor.	Group load factor.
A	34	.53	12	3.6	3.33	7.	23.1
B	185	.53	68	20.	3.40	7.	23.8
C	167	.87	93	28.	3.32	7.3	24.0
Aver.	128	.68	57	17.2	3.35	7.1	23.9

COMMERCIAL LIGHTING.

D	46	1.28	46	33	1.40	13	18
E	79	.74	36	26	1.40	11	16
F	160	.53	62	41	1.51	10	15
Aver.	95	.70	48	33	1.46	10.8	15.7
G	221	2.70	403	270	1.48	13	19

GENERAL POWER.

		H.P.	K.V.A.	K.V.A.			
H	29	1.3	30	21	1.43	15	21
I	18	3.3	40	25	1.60	16	26
J	11	11.8	90	65	1.39	18	28
K	25	6.0	100	70	1.43	21	30
Aver.	21	4.5	65	45	1.44	17.5	26

The observations made and results calculated for the various classes of consumers are presented in Table XIII. Group A is a residence block supplied by one transformer, in which there are 34 consumers having a connected load of 18 kw. or an average of .53 kw. per consumer. The sum of the consumers' maxima is 12 kw., while the actual maximum as

measured on the transformer is 3.6 kw. The ratio of the consumers' maxima to the transformer maximum is 3.33, which is the diversity factor between the consumers in this block. The average load factor of this group of consumers is 7 per cent, considered individually, while the load factor of the energy delivered from the transformer is 23.1 per cent.

Group B is a similar block having 185 consumers with the same average connected load. The sum of the consumers' maxima is 68 kw., the transformer maximum is 20 kw., the diversity factor is 3.4 and the transformer load factor is 23.8.

The premises lighted by these two transformers were practically all apartments and the public halls of the same.

In Group C the premises were about two-thirds small apartments and the remainder large apartments and residences. This accounts for the greater connected load and the larger average load on this transformer. The diversity factor, however, remains practically the same as in the previous cases.

The determination of the sum of consumers' maxima in cases where the connected load is less than 1 kw. is based upon averages worked out from the readings of demand meters. The schedule of individual consumers' demands used in these calculations was as follows:

Connected load 50-watt equivalent.	3	5	7	9	11	13	15	17	19
Maximum 50-watt equivalent.....	3	5	6	6.5	7	8	8	9	10

These maxima were determined from the averages of the demand meter readings of over 20,000 residence consumers.

The transformer maxima were taken by the use of Wright demand meters during the winter months, this being the time when the maximum load occurs in the districts in which observations were taken.

Of the three groups of commercial light consumers, it will be noted that group D consists of 46 consumers having an average connected load of 1.28 kw. The total of the consumers' maxima is 46 kw., the transformer maximum is 33 kw.

and the diversity factor is 1.4. This group consists of small stores on an outlying business street, with several saloons and restaurants.

In group E there are 79 consumers having an average connected load of .74 kw. and a diversity factor of 1.4. There are no large stores in this group and no saloons or restaurants.

In Group F there are 160 consumers with an average connected load of .53 kw. and a diversity factor of 1.5. This group includes eight or ten apartments above stores and an equal number of offices, lodge halls, etc., which tend to increase the diversity factor and to lower the average consumer's load factor.

Group G is an 18-story office building in which there are 221 consumers including the lighting and general power service of the building owner. The connected load of 603 kw. includes 180 horse power in ventilating fans, pumps and such other machinery as is used in an office building having hydraulic elevators. The average load per consumer is 2.7 kw., the sum of the consumers' maxima is 403 kw., the maximum as measured on the feeder at the substation switchboard is 270 kw. and the diversity factor is 1.48. The consumers' maxima were determined from demand meter readings for the most part in this case. This is not strictly commercial lighting, as the power load could not be measured separately and is included in the maximum of 256 kw. for the building.

Among the general power users, group H consists of 29 single-phase consumers having a connected load of 37 horse power and an average load of 1.3 horse power. The sum of the consumers' maxima is 30 kv-a., the transformer maximum is 21 kv-a. and the diversity factor is 1.43. These consumers are sweat shops manufacturing men's clothing.

Group I consists of 18 consumers having 60 horse power in single-phase and three-phase motors whose average horse power connected is 3.3. The diversity factor for this group

is 1.6. Ten of these are single-phase consumers manufacturing clothing and the other eight are three-phase consumers using power for various other manufacturing processes.

Group J consists of eleven consumers having an average load of 11.8 horse power whose diversity factor is 1.39. The largest consumer in this group has wood-working machinery which is operated steadily and accounts for the higher transformer maximum and lower diversity factor.

In Group K, 25 consumers have an average installation of 6 horse power with a diversity factor of 1.43. About fifteen of this group are small clothing manufacturers having less than 5 horse power.

The consumers' maxima for these groups were determined on the basis of maximum demands of several thousand similar direct-current consumers who were equipped with demand meters. The transformer maxima were measured between 10 and 11 A.M., this being the hour when the alternating current power load is a maximum in Chicago.

The consumers' load factors which appear in this table for power users were taken from a paper read by Mr. E. W. Lloyd before the National Electric Light Association at its 1909 convention. His results were derived from a large number of demand and wattmeter readings on various classes of power users.

With large users the larger part of the diversity arises between different parts of the premises. In a large mercantile store there are always some departments where business is dull at a time when it is good in another department and *vice versa.* Likewise in a large manufacturing establishment the requirements of different departments for power vary with different hours of the day and different days of the week. The maximum demands of large users therefore vary by a smaller percentage from day to day than those of small consumers,

and the principal source of diversity between large users arises from differences in the general character of their requirements.

The curves in Fig. 172 show the result of combining the demands of a large day power users and a large evening light users. The sum of the demands of these consumers is 1150 kw.,

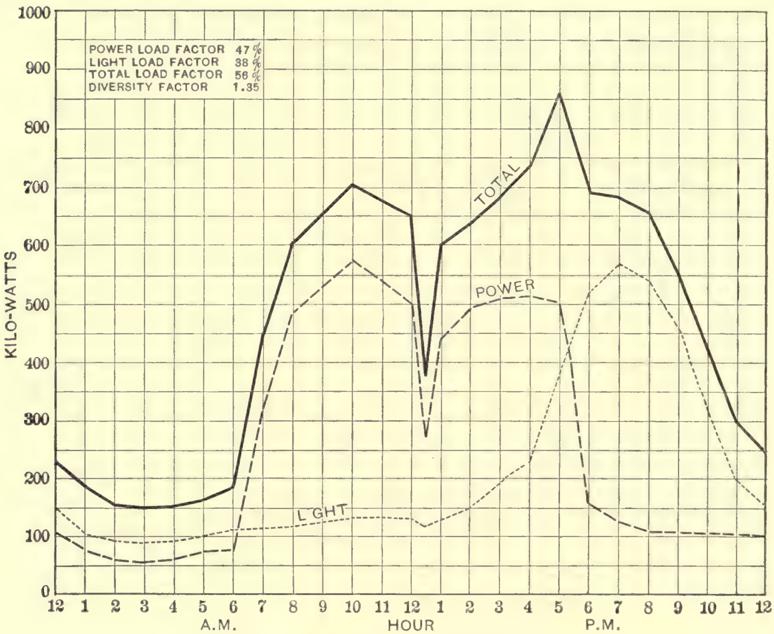


Fig. 172. Diversity between Light and Power Loads.

while the coincident maximum demand, which occurs at 5 P.M., is but 850 kw. The diversity factor between these groups of consumers is therefore 1.35.

Diversity between Transformers. — The diversity between different transformers on the same feeder is similar to that between large users. A study of the amount and character of load on the various transformers in conjunction with rep-

resentative tests of transformer loads makes it possible to derive diversity factors for groups of transformers which are reasonably accurate.

Analyses made of transformers supplying residence territory with about 25 per cent of small store lighting and less than 5 per cent of power load indicate an average diversity factor between transformers of 1.2. Transformers supplying about equal amounts of residence and commercial lighting with 25 per cent of power show diversity factors of about 1.3. Those supplying a large number of scattered power consumers with 40 per cent to 50 per cent of lighting may have diversity factors of 1.8 to 2 between transformers.

Diversity between Feeders. — At the substation bus bar there is a further diversity between feeders. In a certain substation having a load of 3500 kw. which is 90 per cent lighting, the maximum loads on most of the feeders occur at 7.30 P.M. in December, the other feeders having their maxima at 5 P.M. The diversity factor of the feeders in this station during the week of the maximum load of the year was 1.05.

In a 2700-kw. substation the maximum load on 90 per cent of the feeders occurs at 5 P.M., due to a large proportion of store and factory light and power, and the diversity factor between feeders was 1.06 during the week of the maximum load of the year.

In two other substations of nearly the same size about 60 per cent of the feeders have 7.30 P.M. maxima and 40 per cent have 5 P.M. maxima. In these substations the diversity factor was 1.14 and 1.15 respectively during the week of the annual maximum.

In another case where about half of the feeder maxima occur at 5 and half at 7.30 P.M. the feeder diversity factor was 1.36.

Substation Diversity. — In systems having five or more substations there is an appreciable diversity factor of the group in the average system. This arises from the fact that certain substations have larger proportions of power and industrial load than others, and the day and hour of their maximum demand differs from those which serve lighting load in predominance.

This is illustrated by the following table, showing the substation maxima of 10 Chicago substations, together with the demand upon the generating station coincident with the total system maximum load and the individual diversity factors of each substation.

Substation.	Absolute maximum kw.	Coincident demand.	Indiv. div. fact.
1	1,900	1,800	1.06
2	1,400	1,170	1.26
3	590	400	1.47
4	1,740	1,350	1.29
5	3,550	2,750	1.29
6	1,740	1,550	1.12
7	1,570	1,280	1.23
8	4,000	3,900	1.03
9	1,690	1,500	1.13
10	1,670	1,600	1.04
Total	19,850	17,300	1.15

The diversity factor of the group is the sum of the absolute maxima, 19,850 kw., divided by the sum of the coincident demand, 17,300, or 1.15. It will be noted that some of these substations have very small individual diversity factors while those of others are relatively large.

In systems supplying an appreciably large proportion of electric railway service there is a considerable diversity factor arising from the fact that railway service demands are transferred from substations near the center of the city to those in the outskirts as the cars progress outwardly during the evening rush hour. The reverse progress takes place in the morn-

ing peak but is not concentrated so closely as the evening peak and usually does not fix the maximum demand of the railway portion of the load.

Total Diversity. — The total diversity factor of the generating and distributing system is the continued product of the diversity factors between consumers, transformers, feeders and substations. In the case of residence consumers, the total diversity factor is the product of $3.35 \times 1.3 \times 1.15 \times 1.1$. This amounts to 5.52. For commercial lighting consumers the total diversity factor is 2.41. For general power consumers the total diversity factor is 2.26 and for large users 1.45. These are the diversity factors from the consumer's meter to the generating station.

The average diversity factors for the four classes of consumers and the total diversity factor from the consumer to the generator are presented in Table XIV.

The total diversity factor of a distributing system is obtained by combining those of the various classes of consumers. In the Chicago system the diversity factor of the general lighting and power load, not including electric railways, is 3.2.

TABLE XIV. — DIVERSITY FACTORS.

	Residence light.	Commercial light.	General power.	Large users.
Between consumers	3.35	1.46	1.44	....
" transformers	1.3	1.3	1.35	1.15
" feeders	1.15	1.15	1.15	1.15
" substations	1.1	1.1	1.1	1.1
Consumer to transformer	3.35	1.46	1.44	....
" " feeder	4.36	1.90	1.95	1.15
" " substation	5.02	2.19	2.24	1.32
" " generator	5.52	2.41	2.46	1.45

Relation to Load Factor. — The relation of the group diversity factor to group load factor is direct and comparatively simple. When, for instance, a group of retail users is con-

sidered, the load factor at the transformer supplying the group is the product of the average individual load factor by the group diversity factor. With 100 residence users having a yearly group diversity factor of 3, and an average annual load factor of 7 per cent, the annual load factor at the transformer is $3 \times 7 = 21$ per cent.

To state it in another way, if the average annual consumption of the members of the group is 250 kilowatt-hours, and the average annual load factor of each is 7 per cent, the average maximum demand of the individual user is $\frac{250}{.07 \times 8760} = 0.408$ kilowatts. The sum of the 100 individual demands is therefore $100 \times 0.408 = 40.8$ kilowatts. Since the yearly group diversity factor is 3, the coincident demand at the transformer is $\frac{40.8}{3} = 13.6$ kilowatts. This transformer delivers $100 \times 250 = 25{,}000$ kw. hrs. per year to the group and its annual load factor as a wholesale consumer on the distributing system is $\frac{25{,}000}{13.6 \times 8760} = 21$ per cent.

This rule may be applied to any class or group of users whose average individual annual load factor, annual consumption, and yearly group diversity are known. It is equally applicable to a group of substations in a large system.

The energy converted in the group of substations amounts to 53,200,000 kw. hours annually, and the annual load factors vary from 19 per cent to 35 per cent, the average being 30.6 per cent.

The group diversity factor being 1.15, the annual load factor at the point of supply is $30.6 \times 1.15 = 35.1$ per cent.

This may be shown also from the annual output and coincident demand, the output being 53,200,000 and the demand being 17,300 kw.

$$\text{Load factor} = \frac{53{,}200{,}000}{17{,}300 \times 8760} = .351.$$

There is no direct relation between the individual diversity factor and the individual load factor, except that consumers having a high load factor are more likely to come on the peak and hence to have a small diversity factor and *vice versa*. The off peak consumer may, of course be an exception to this rule as he may have a relatively high load factor, but also a high individual diversity factor because of the special contract arrangement not to use energy at the usual hours when the system maximum load comes on.

In the table of substation maxima, the first one in the list has an annual load factor of 35 per cent but its maximum comes so nearly coincident with that of the whole system that its diversity is small, the individual diversity factor being only 1.06. The second one in the list has an annual load factor of 37 per cent and yet its individual diversity factor is 1.26, because its maximum load occurs at a different hour from that of the general system. Thus one of these substations has a diversity factor higher than that of the group, while that of the other is lower, though their load factors are about the same.

Relation to Investment. — The effect of diversity factors upon the various parts of the generating and distributing plant is to reduce investment and hence the demand portion of charges for service. This effect is so material as to justify the most careful analysis of load conditions in their relation to diversity of demand. Such analyses are of value in solving the problems incident to fixing equitable rates for various classes of service, in making subsequent adjustment of established rates, and in revealing the relative rates of returns produced by various classes of users under existing rate schedules. It is of the utmost importance that the methods pursued in determining the cost of electric service be based upon correct principles and that the data at hand be intelligently applied.

As a basis of illustration, it will be assumed that an alter-

nating-current central-station system has been developed to a point where it has 25,000 kilowatts in generating plant capacity and a maximum load of 20,000 kilowatts at a cost of $8,100-000 or $405 per kw. load.

The apportionment of the capital invested is further assumed to have been made as shown in Table XV. This apportionment is roughly representative of an average system in a medium-sized city without any considerable suburban distribution. In a district supply system covering a large area of scattered towns and cities, the transmission system would be a larger percentage of the total and other parts might be materially different. The numerical values derived from these figures as a basis are therefore to be considered only as applying to a system of the type assumed, and, being hypothetical, should be considered merely as illustrating the method of calculation.

TABLE XV.—ASSUMED ALTERNATING CURRENT CENTRAL STATION SYSTEM.

	Group Div.		Kw. useful load.	Full load eff.	Actual kw. demand.	Invest-ment per kw.
	Investment.	Factor.				
Generating station ..	$2,350,000	...	16,050	....	20,000	$117.50
Transmission system.	450,000	...	.....	0.95	......	21.50
Substation...........	800,000	1.1	17,650	0.912	21,000	38.00
Distribution lines....	2,750,000	1.15	20,300	0.802	23,200	119.00
Transformers........	350,000	1.3	26,400	....	26,400	13.00
Meters...............	500,000	...	.....	....	......	......
Miscellaneous........	900,000	...	.....	....	......	......
Total.............	8,100,000	...	.....	0.802	......	......

The actual kilowatt demand which appears in the next to the last column is the net result of the application of both diversity factor and full-load efficiency. The 20,000-kw. load on the generating station is made up of 16,050 kilowatts of useful load and 3950 kilowatts of losses in the transmission, conversion and distribution systems. If the efficiencies are

assumed at 95 per cent for the transmission system, 96 per cent for transformer substations and 88 per cent for the distribution system, the net overall efficiency would be 80.2 per cent.

If there were no losses, the "actual kw. demand" would be the same as the "useful load."

If the losses are taken into account:

The sum of the feeder maxima at 88 per cent efficiency is

$$\frac{26{,}400}{1.3 \times 0.88} = 23{,}200 \text{ kilowatts.}$$

The sum of the substation maxima at 96 per cent efficiency is

$$\frac{23{,}200}{1.15 \times 0.96} = 21{,}000 \text{ kilowatts.}$$

The maximum at the generating station at 95 per cent efficiency is

$$\frac{21{,}000}{1.1 \times 0.95} = 20{,}000 \text{ kilowatts.}$$

These are the loads which would be observed in this system at each point where the group of elements is supplied.

The investment per kilowatt in the last column is determined by using the kilowatt actual demand at the point of supply, as shown in the previous column.

From this data the investment required to serve a given class of consumers may be determined, if the group diversity factor of the class is known, and with the investment determined, it is but a step to determine what the demand portion of the charge to that class of consumers should be.

In the distributing system investment, there are, however, such wide variations of the cost per kw. under different conditions that some attention should be given to the costs for classes of users which are materially higher or lower than the average.

The investment per kw. is very greatly affected by the density of the load, that is, by the load served per square mile. For instance, in outlying districts where there are less than 10 consumers per block, the investment may often be as much as $300 per kw. for distribution, and in manufacturing districts or retail business districts, it may be as low as $60 or less. This is due in large measure to the fact that pole lines or conduit lines, primary mains and secondary mains must all be installed before any consumer can be served. The minimum capacity which it is possible to install for mechanical reasons is so great that the initial equipment remains the permanent equipment in many portions of the city, and additional consumers increase the load density without adding proportionately to the investment. The kw. per square mile can be increased tenfold above its initial value in many cases without necessitating additional investment except for feeders, transformers and service connections. These reinforcements cost only $25 to $40 per kw. and thus tend to lower the average cost per kw. as load is added. In a similar way, large users may be taken on at only the cost of feeder and transformer capacity and the distribution investment for consumers whose load is 200 kw. and upward is frequently as low as $50 per kw. Thus, for retail users, the investment per kw. in the distribution system here assumed would be from $50 to $200 in order to make the average of the whole system $119 per kw.

Investment for Residence Consumers. — When it is desired to determine the investment required for residence consumers, for instance, and it is known that the group diversity factor of this class is 3, the result may be reached approximately as follows: Assume that 100 such consumers are to be served and that their average individual maximum demand will be .6 kw. The sum of the individual demands is then $100 \times .6 =$

60 kw. and the group diversity factor being 3, the demand on the transformer is $\frac{60}{3} = 20$ kw.

The group diversity factor of the transformers being 1.3, the demand on the feeder will be $\frac{20}{1.3} = 15.4$ kw., plus losses at 98 per cent efficiency, or $\frac{15.4}{.98} = 15.7$ kw.

The diversity factor of the feeders being 1.15 and the efficiency of the distributing circuits being 90 per cent, the demands on the substation will be $\frac{15.7}{1.15 \times .90} = 15.2$ kw.

The demand on the power station at the time of the maximum load on the system, with a substation diversity factor of 1.1 and an efficiency of 90 per cent for transmission and conversion equipment, would be $\frac{15.2}{1.1 \times .90} = 15.3$ kw.

The investment required to carry this group of consumers therefore is summarized as follows, using the units of cost assumed, in the above table, and taking meters at $7.00 each.

100 meters @ $7.00	$700.00
20 kw. transformers @ $13.00 per kw	260.00
15.7 kw. distribution line capacity @ $200 per kw	3140.00
15.2 kw. substation capacity @ $38.00 per kw	577.00
15.2 kw. transmission line capacity @ $21.50	327.00
15.3 kw. generating station capacity @ $117.50	1798.00
Miscellaneous investment, 12.5 per cent	850.00
	$7652.00

Total investment per kw. gen. sta. load	$500.00
Total investment per kw. consumers demand	127.50

If the fixed charges on the investment in the plant are taken at 13 per cent, the demand portion of the cost of serving the residence consumer in this group is $.13 \times \$127.50 = \$16.57$ per annum, or \$1.36 per month per kw. of demand at the consumer's premises. For the average residence consumer here assumed to have a maximum demand of .6 kw., the demand cost is $.6 \times \$1.36 = \$0.81$ per month.

This, of course, does not include any operating cost or consumer cost, but is purely that portion of the cost due to the fact that the consumer's demand requires a certain portion of the plant to be reserved for his use.

Investment for Commercial Consumers. — In the case of commercial lighting and power consumers of the retail class, the diversity factor is lower and the plant required is somewhat more for a consumer having the same individual demand.

Assuming a group of 100 commercial light and power consumers, having loads of less than 10 kw. and whose individual demands average 3 kw., the investment cost per kw. for the distribution system is somewhat less and may be taken at \$150 per kw.

The demand at the transformer, with a group diversity factor of 1.4, is $\frac{3 \times 100}{1.4} = 214$ kw. The load on the feeder at 98 per cent transformer efficiency and 1.3 diversity factor of transformers is $\frac{214}{.98 \times 1.3} = 165$ kw. At the substation the load is $\frac{165}{.90 \times 1.15} = 159$ kw. and at the generating station it is $\frac{159}{.9 \times 1.1} = 161$ kw.

The investment may be summarized as follows:

100 meters at $9.00 each................	$900.00
214 kw. transformer capacity @ $13.00....	2,782.00
165 kw. of distributing line capacity @ $150	24,750.00
159 kw. of substation capacity @ $38.00..	6,042.00
161 kw. of transmission capacity @ $21.50	3,461.00
161 kw. of generating capacity @ 117.50..	18,917.00
Miscellaneous investment @ 12.5 per cent	7,100.00
	$63,952.00

$$\text{Investment per kw. generating station load} = \frac{63{,}952}{161} = 400.00$$

$$\text{Investment per kw. consumer's demand} = \frac{63{,}952}{300} = 213.00$$

It is to be noted that the meter investment is a much smaller part of the total investment required for this class of consumers than it is for the small residence consumer. The meter investment for this class is but $3.00 per kw. of consumer's demand while for the small residence consumer it is $11.66 per kw. The fixed charges are $.13 \times 213 = \$27.70$ per annum or $2.31 per kw. per month, or $6.93 for a 3 kw. consumer.

In the case of the wholesale user with a demand of about 200 kw. or more, the feeder and a small proportion of the primary main system are the only parts of the distribution system needed to meet his requirements aside from transformers. The total value of these will be taken at $50 per kw. in this case. The total investment would be as follows for a consumer having a 200 kw. demand and an individual diversity factor as related to the substation of 1.25:

Metering equipment..................	$30.00
Transformers, 225 kw. @ $7.00 per kw...	1,575.00
Distribution line, 160 kw. @ $50 kw.....	8,000.00

Substation capacity,

$\frac{160}{.90 \times 1.15} = 154$ kw. @ \$38................ 5,852.00

Transmission capacity,

$\frac{154}{.9 \times 1.1} = 155$ kw. @ \$21.50.............. 3,242.00

Generating capacity, 155 kw. @ \$117.50......... 18,212.00

Miscellaneous investment, 12.5 per cent........ 4,620.00

Total................................ \$41,531.00

Investment per kw. generating station load $= \frac{41,531}{155} = \$270.$

Investment per kw. consumer's demand $= \frac{41,531}{200} = \$207.$

Thus the fixed charges for the wholesale consumer are $.13 \times 207 = \$26.91$ per kw. of consumer's demand per annum.

In case the wholesale consumer requires a class of service which has a higher diversity factor than 1.25, this element of the cost may be still further reduced. For instance, in the case of long hour users such as ice manufacturers who can arrange their hours of operation so as to shut down most of their plant during the hours of the day in the months of the year when the general system maximum occurs, it is possible to eliminate the greater part of the charge for generating station capacity and in some cases the transmission line and substation investment. This may amount to approximately one-half the total investment.

Principles of Rate Making. — The establishment of rate schedules which are equitable to the consumer, profitable to the investor and competitive with other forms of light and power service is a most important part of the conduct of a public utility business.

The profit to the investor and the ability of a given rate to compete with other forms of service are known quite definitely in any going concern, but the determination of what is equitable to the consumer is not a simple problem since it involves an analysis of the cost of service under the particular conditions obtaining in the community in question.

Under public utility commission government, the problem usually resolves itself into a determination: (*a*) of the rate of return made by the property during recent years, (*b*) the establishment of a fair rate of returns in view of the hazards of the business, and (*c*) an adjustment of the existing rates with a view to making the income from the various principal classes of consumers produce as near as possible the rate of return which it has been decided is fair to the investor.

Rate of Return. — In determining the rate of return which has been made by the utility in the years immediately preceding, the first value to be established is that of the physical property of the utility. This should be taken from existing records and a sufficient inventory to establish the accuracy of the records where possible. Where early records are not available, as is sometimes true of companies which were formed by the consolidation of several small companies, the value of the property must often be determined by complete inventory and appraisal. This involves a large expense of time and labor if done thoroughly enough to be fair to the investor. In some states the commissions follow the policy of working from records as far as possible, while other commissions rely upon records to a very limited extent and make valuations by inventory and appraisal in the majority of cases.

The decision as to what is a fair rate of return to the investor is based upon general considerations of financial and industrial environment. If industrial conditions are variable through a wide range, the utility should be permitted to earn

a higher rate than where conditions are more stable in order that the low rate of earnings in years of depression will be offset, and a fair average maintained over a period of years.

The condition of money markets, the hazard from floods where water power is utilized, and the hazards incident to the use of overhead lines are all factors which must be considered. The utility must be allowed to earn sufficient to accumulate suitable reserves to enable it to take care of these various contingencies, if it is to endure and the investors' interests are properly conserved.

Commissions have established rates of return at 6 to 7 per cent in eastern states and as high as 8 per cent in some cases in western states.

Rate Adjustments. — Having determined the value of the property and the amount of the necessary working capital upon which the fair rate of return is to be made, the difference between the actual earnings and the earnings which are considered fair is at once known. In a growing property this is usually a surplus calling for a reduction of rates. However, in some cases where competition has reduced prices recklessly to a point which has wiped out all or part of the legitimate profits of the undertaking, the difference is a deficit and certain of the rates must be increased.

The problem then resolves itself into the task of classifying consumers according to the character of service rendered and making a revision of such of the rates as appear to be most profitable (or least profitable if an increase is necessary). Having determined how much of the total income each class of consumers has contributed it is a comparatively simple matter to make adjustments which would have produced the desired decrease (or increase) in the income, if they had been in effect during the previous year.

However, although this adjustment may be very simple it is

the most vital part of the rate fixing procedure. If the adjustments are not properly applied, they fail to give the consumer a fair share of the reduction and they may prove to be unfair to the investor. The problem thus involves an analysis of the cost of service to the principal classes of users and what is equally important the use of a rate system which automatically varies in a manner which follows the variation of cost as closely as possible.

The "cost of service" must necessarily be the basis of any rate which is profitable to the investor, but there are certain classes of service in which the "value of the service" must be considered. The value of the service is in some cases so low that the general rate schedules are too high to attract the business. In some such cases it is possible to establish rate schedules containing special limitations such as the requirement that no energy shall be used during "peak hours" which reduce the cost to the consumer to a point where the value of the service makes it attractive to him. The manufacture of raw water ice is an illustration of this. In some cities "off peak" rates have been established for this and any other class of users who are able to control the use of energy so that it will not be used during peak hours. On the other hand, there are cases where the value of the service to the consumer is such that the general rates involve an expense far less than the value of the service and little question is raised as to the fairness of the charge which perhaps includes more than the average proportion of profit.

The *value* of the service is thus a factor as well as the cost of the service in the making of rates.

The Cost of Service. — The cost of electric service is made up of three principal parts: (*a*) the fixed charges on the necessary plant and distributing system, (*b*) the production cost of the energy together with the cost of conversion and dis-

tribution and (*c*) the cost of metering, billing, collecting, accounting and other expenses which are proportioned to the number of consumers served. There are also certain general expenses which are proportional roughly to the size of the business and may be classed with fixed charges.

In determining the cost of service, the cost of production, distribution and management is readily found from existing records of the utility, if they have been properly kept. From these the average cost per kw. hour and the average cost per consumer for handling his account may be established.

The determination of the fixed charges due to the investment needed to supply the consumer's demand is, however, not capable of ready evaluation, since the investment per kw. of demand varies through very wide limits and the use of averages is not desirable except in dealing with the larger classes of small consumers.

The fixed charges which include interest, depreciation, taxes, insurances, etc., on the investment are calculated at a rate which is fair to all when the investment per kw. of demand is known for the class of consumers under consideration.

The investment per kw. is different for the various classes because of the differences in the density of load distribution and because of the diversity factor.

This is fully illustrated in the discussion of diversity factor in the early part of this chapter, where the investment per kw. of demand is worked out for residence and other classes of consumers in a hypothetical central station system.

It is obviously impracticable to work out the demand cost of every class of consumers separately as the necessary data of demand and diversity are not available.

In the case used for illustration the investment for residence consumers was found to be $500.00 per kw. of demand on the generating station, or $127.50 per kw. of demand at the consumer's premises. The demand cost was also found to be

\$16.57 per year per kw. of demand at the consumer's meter. As this is the point at which the demand is taken in practical rate systems the demand cost must be based upon the investment per kw. of demand at the meter rather than at the source of supply.

The total cost of service to residence customers under the conditions assumed for illustration is \$16.57, plus the cost of operation, plus the cost of handling the account. To these must be added a percentage for general expenses not included in any of the other items.

The "customer" cost includes the expense of metering, billing, collecting, bookkeeping, the cost of handling retail customers, who move from place to place, and the new applicants. In some cities the "moving" item is one which involves a considerable expense each spring and fall. The cost of all these items usually runs from \$4.00 to \$5.00 per year per consumer.

The "operating" cost includes the cost of fuel, labor and supplies for producing the energy, for converting it at substations, for distribution, and for the necessary maintenance and repairs of the entire generating, converting, transmitting and distributing plant.

An analysis of these operating costs reveals the fact that they are only partially proportional to the kw. hours produced.

In the power station, much of the labor is a fixed charge as it must be on hand regardless of the number of units in operation. This may be from 25 to 50 per cent of the total labor item of the station, it being smaller in the larger stations and *vice versa*.

In substations nearly all of the labor of attendance is independent of the output and is a fixed charge.

In the transmission and distribution system the labor of attendance and maintenance such as fuse renewals, wires down and the like is proportional to the mileage of lines rather than

to the kw. hours carried over them. As the mileage is proportional to investment in lines, the large part of the cost of maintaining distribution lines is in the nature of a fixed charge, rather than a kw. hour charge. This amounts to about 1 per cent on the investment in underground lines and about 4 per cent on overhead lines.

In a plant of the size used here for illustration, the fixed portion of the operating expense is about 40 per cent of the total.

Assuming that the total cost per kw. hour for the operating expense items, not including consumer costs or general expense, is taken to be 1.5 cents per kw. hour, that the annual load factor is 30 per cent for the entire system, and that the fixed portion of the operating expense is 40 per cent or 0.6 cent per kw. hour at the annual load factor, then the cost which is proportional to the kw. hours is 0.9 cent per kw. hour.

A load factor of 30 per cent is equivalent to $.30 \times 8760 = 2628$ kw. hours per kw. of generating station demand per annum. At 1.5 cents this represents a cost of $39.42 per year, of which $.006 \times 2628 = \$15.77$ is the operating fixed charge per kw. per year.

The general expenses include executive supervision, legal expense, taxes, insurance, advertising, and other miscellaneous expenses of a general character. These vary somewhat in different localities and with the size of the company, being 25 to 40 per cent of the total running expense.

In a company having a system such as that used for illustrative purposes in this case, it will be assumed that general expense is 33 per cent of the total running expense, or 50 per cent of the sum of the operating and consumer costs.

Summarizing the various costs as determined for the residence consumer and assuming that his annual consumption is 600 kw. hours per kw. of demand, they are as follows·

Demand cost, 13 per cent of $127.50	$16.57
Fixed operating cost	15.77
600 kw. hours at .9 cent	5.40
Consumer cost	5.00
General expense, 50 per cent of oper. and consumer cost	13.08
Total	$55.82 per kw. year

The average cost is $\frac{5582}{600} = 9.30$ cents per kw. hour.

In the case of a commercial consumer having a consumption of 1000 kw. hours per annum, per kw. of demand the cost is

Demand cost, .13 × 213.00	$27.70
Fixed operating cost	15.77
1000 kw. hours at .9 cent	9.00
Consumer cost	5.00
General expense	14.88
Total	$72.35

The average cost is $\frac{7235}{1000} = 7.23$ cents per kw. hour.

The cost per kw. hour, of course, varies with the load factor as the portion of the cost which increases with longer hour use is only 20 per cent of the total running expense.

This variation of the rate per kw. hour is as follows for the commercial consumer in this case.

Load factor per cent	5	10	15	20	30	40	50
Rate per kw. hour	18.3	10	7.1	5.6	4.2	3.4	3

Rate Systems. — The rate problem consists in the establishment of schedules which meet the commercial requirements, will be sufficiently above cost to be fair to the investor and yet not so much above as to be unfair to the user of electric service.

It is apparent from the way in which the cost varies with the load factor that the rate system should be so constructed that the rate is automatically reduced as the load factor increases and *vice versa*.

In the early street lighting systems where the hours of burning were fixed by contract a fixed price per lamp per month or year was very common, this being known as a flat rate. The absence of metering devices and lack of understanding of cost were responsible for the application of flat rate systems to incandescent lighting when it was first introduced, but without restriction as to burning hours.

This led to abuses which were expensive and it was seen that some form of metering was desirable. The most available meters were those which recorded ampere hours or kilowatt hours, and the natural result was a system of rates based on these units. Where ampere hour meters were used it was usually assumed that constant potential was maintained at the meter and the bill was rendered in 50-watt lamp hours or in kw. hours. Thus the kilowatt hour became the unit upon which rates were based, though but a small part of the cost of the service was proportional to the number of kilowatt hours used. As consumers became larger and the hours use longer it was necessary to introduce discounts for quantity in order to compete with other forms of light and power.

In England, in the year 1892, Hopkinson made an analysis of costs showing that the demand cost was a large factor and that the rate for the energy used could be made very low if the demand cost were first assured. A little later Wright devised a meter for measuring the consumer's demand based upon the expansion of gas in a bulb by the heat of the current used by the consumer. This meter was the first demand meter developed for commercial use and it has been employed in England and America in considerable numbers by the companies which adopted demand systems of rates.

The use of a demand meter on retail installations below about 2 kw. was, however, found expensive and undesirable. After a sufficient amount of data had been secured as a basis for determining the average demand factor of various sizes of installation and classes of users, the demand of smaller users was fixed as a percentage of the connected load, and not measured. This practice was adopted by companies which had never used demand meters, thus enabling them to use a demand system of charging.

In 1900, H. L. Doherty made a similar study in which he carried the analysis a step farther and showed that with small users it was important that the "customer" cost be considered as an element of the rate.

It is usual to apply this by including it in the demand charge, but with the provision that in months where there is little or no use of electricity, the consumer must pay a minimum charge. With power installations it is also usual to apply a minimum charge of about 50 cents per H.P. per month, to cover the demand and customer costs when no electricity is used.

In residence installations it has been found practical in some cities to make a demand charge based on the number of "active rooms" in a residence. This tends to encourage free use of light in basements, closets and similar places where they are not included in the demand charges, whereas a demand charge based solely on the number of lights installed, has the opposite tendency.

There are other modifications of rates which are in general use, the two most common being the "step" rate and the "block" rate.

The "step" rate charges one rate, say 12 cents for any monthly consumption of electricity up to 50 kw. hours, 10 cents for any consumption over 50 and less than 100 kw. and so on reducing the rate gradually as the consumption increases.

This takes no account of the size of the installation and is applied to certain classes as a rule so as to minimize discrimination against the long hour user.

The "block" rate charges one rate, say 12 cents for the first 15 kw. hours per month, 10 cents for the next 25 kw. hours and so on down the scale. This also ignores the demand and results in discrimination, if not carefully applied.

The demand system, being based upon the cost of service, has the advantage that a single rate schedule can be applied to all ordinary service, without establishing any considerable

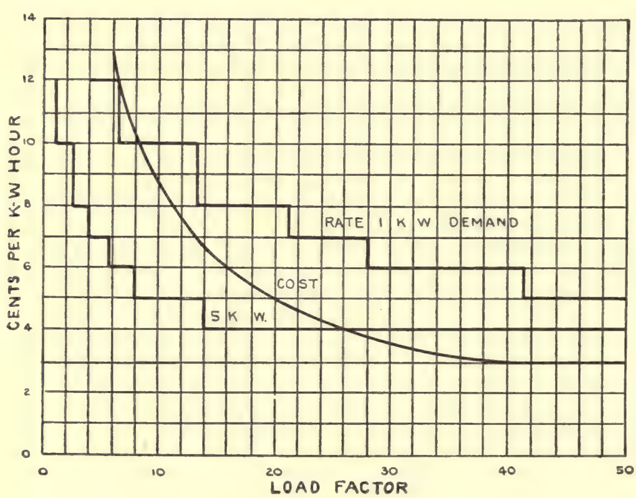


Fig. 173. Step Rate.

number of classes. A demand system of rates is the most equitable to all consumers and at the same time gives the utility a fair return.

It is important, however, that where estimated demands are used instead of measured demands, that they be based upon experience with a large number of consumers, in order that they represent a fair average, and that all users of the same

class be treated alike. It is usual to establish a schedule of demands for residences, another for stores and offices, another for retail power users and sometimes one for large power installations.

The net result of the operation of the various forms of rates here described may be illustrated graphically to advantage. The diagrams, Fig. 173, show the net cost per kw. hour on a step rate to a consumer using energy at the maximum rate of one kw. as compared with one using five kw. at different load factors or hours daily use.

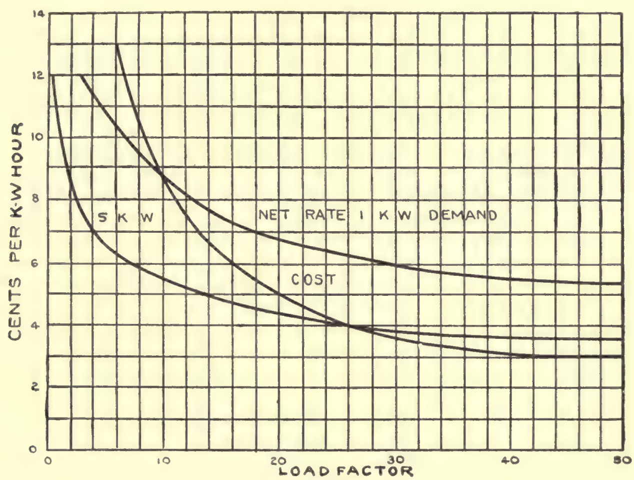


Fig. 174. Block Rate.

The step rate is as follows:

1 to 50 kw. hours at	12¢
51 to 100 kw. hours at	10¢
101 to 150 kw. hours at	8¢
151 to 200 kw. hours at	7¢
201 to 300 kw. hours at	6¢
301 to 500 kw. hours at	5¢
Over 500 kw. hours at	4¢

The smooth curve shows the variation of the cost of serving these consumers, on the assumptions of a demand cost of \$27.00 per annum per kw., a consumer cost of \$9.00 per annum, fixed operating costs of \$16.00 per annum per kw. of demand, and other operating expense at 1.5 cents per kw. hour.

In a similar way the variation of the net rate to two similar consumers supplied on a block rate schedule is shown in the curves in Fig. 174, together with the cost curve.

The block rate which these curves represent is stated as follows:

12¢ per kw. hour for the first block of 15 kw. hours.
10¢ per kw. hour for the next block of 15 kw. hours.
8¢ per kw. hour for the next block of 20 kw. hours.
6¢ per kw. hour for the next block of 50 kw. hours.
5¢ per kw. hour for the next block of 100 kw. hours.
4¢ per kw. hour for the next block of 300 kw. hours.
3¢ per kw. hour for all over 500 kw. hours.

Fig. 175 shows a similar comparison between a demand rate and the cost curve, the demand rate being as follows: 12 cents per kw. hour for an amount of energy equivalent to 36 hours use per month of the demand; 6 cents per kw. hour for an amount equivalent to the next 30 hours use of the demand and 3 cents for all over these amounts.

It is at once evident that with the step rate or the block rate the consumer having the larger demand has a decided advantage over the smaller consumer. On the step rate the 5 kw. consumer gets the same rate at a load factor of 10 per cent as the 1 kw. user at any load factor of more than 40 per cent.

On the block rate the comparison is slightly more unfavorable to the long hour user having a small demand.

Furthermore it is evident from the comparison with the cost curve that the consumer having the larger demand and

smaller load factor is carried at a loss the burden of which is carried by the long hour user having a small demand.

With the demand rate, on the other hand, the variation of the rate to the consumer is the same for any size of consumer up to 10 or 15 kw. provided the load factors are the same.

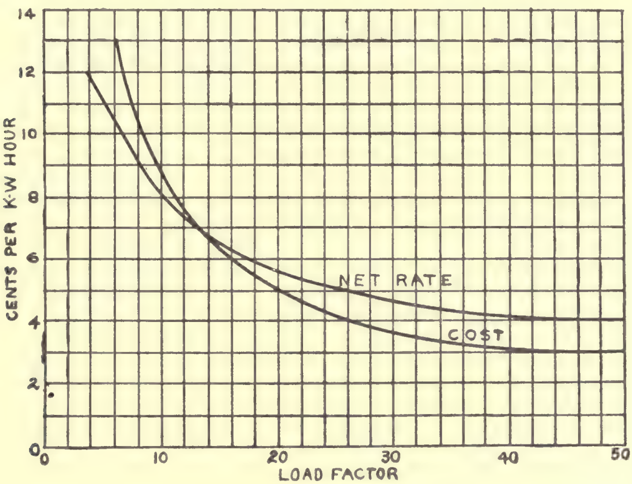


Fig. 175. Demand Rate.

The cost curve follows the rate curve quite closely throughout most of the working range. The very short hour user pays less than cost in each rate system as the tendency of rate regulating bodies is to reduce the maximum rate in response to public demand.

With step and block rates it is necessary, in order to minimize the discrimination between larger and smaller users, to have separate rate schedules for each general class of consumers.

Thus for residence consumers the number of kilowatt hours per block is made smaller so that the long hour user and the user of heating utensils may receive such energy as he uses above the average consumer of his class at a lower rate. Likewise retail commercial users must be served on a different schedule

from the larger users, and separate classes must be maintained for churches, hotels and others.

With the demand system, no classification is needed except as between retail and wholesale, light and power, off peak and on peak, etc.

There are various modifications of these types of rates introduced for the purpose of making the rate fit certain conditions or in some cases for the purpose of making rate reductions. The most common modification is the use of a discount or a scale of discounts. These may be applied to bills above a certain amount, or to the demand charge when the demand exceeds a certain amount, or to the kilowatt hour charge when it exceeds a given amount.

With wholesale demand rates it is usual to express a demand rate as a fixed demand charge plus a rate per kw. hour for the energy consumed, as, for instance, $3.00 per kw. of demand per month, plus 5 cents per kw. hour for the first 1000 kw. hours, 3 cents for the next 2000 kw. hours and 1.5 cents per kw. hour for all consumption over 3000 kw. hours. This virtually introduces a form of block rate into the energy portion of the demand rate. The same thing is sometimes done in the demand portion of the charge, such as $3.00 per kw. per month for the first 50 kw., $2.70 for the next 150 kw., $2.50 for the next 200 kw. and $2.25 for all over 400 kw. These modifications are usually introduced for the purpose of making one rate schedule cover a wide range of sizes of consumers, and to keep the proper relation between rate and cost curves.

In large wholesale rate schedules it is usual to measure the demand by meters of a suitable type and to provide that the highest demand taken in any previous month shall be the demand used in determining the demand charge until such time as a higher demand has been made, when the demand charge will be increased accordingly.

This practice is based upon the principle that plant capacity

must be provided for the increased demand, and the demand charge must be made to cover the increased charges.

When demands are measured it is usual to specify a time interval such as 15 minutes, 30 minutes, or 1 hour during which the demand was made. If the load is steady the time interval is not so important, but with variable demands the time interval is a material factor in determining the demand charge. The demand charge is based upon the average value of the demand during the specified period, so that it is in general higher when a 15-minute period is taken into consideration than when it is averaged over 30 or 60 minutes.

For a similar reason it is not practical to measure the demand of such variable power apparatus as hoists, welders, and small electric railways. Where these are served on a demand rate, the demand must be fixed at a fair value considering the plant capacity reserved for them.

CHAPTER XIV.

PROPERTIES OF CONDUCTORS.

The fundamental unit in electrical distribution is the conductor. A thorough knowledge of the physical properties of the conductors of electricity is therefore indispensable to the distribution engineer.

While all metals are conductors of electricity, each has its own characteristics of resistance, temperature-coefficient and mechanical strength.

Copper being among the best conductors and sufficiently plentiful in nature, is the metal most commonly employed for distribution work. Aluminum is used in transmission work to some extent, because of its low specific gravity. Iron is used as an electrical conductor for rural lines and in railway work, where the rails carry the return current to the power house, and in third rail systems the supply to the motor cars is so carried.

German silver and other alloys are used in making resistance coils for rheostats carrying small currents. Silver is a better conductor than copper, but its value is too great to permit its use for electrical work, except for special purposes where no considerable quantity is required.

Area of Cross-section. — The area of cross-section of wires is commonly measured in circular mils, a circular mil being the area of a wire having a diameter of .001 inch. A circular mil therefore has an area of $.785 \times (.001)^2 = M$. A wire having a diameter of 325 mils or .325 inch has an area of $.785 \times (.325)^2 = M \times (325)^2$. The area of a wire having a diam-

eter of .325 inch is therefore 105,500 circular mils, which is the area of No. 0 wire A.W. gage.

The cross-section of a wire in circular mils is therefore the square of its diameter expressed in mils. The area of a conduct or 1 inch or 1000 mils in diameter is 1,000,000 circular mils.

Likewise, in reckoning the area of rectangular conductors, the area in square mils is the product of the width by the thickness expressed in mils. A square mil is $\frac{1}{.7854} = 1.274$ times a circular mil, and a circular mil is .7854 of a square mil. It is customary to express areas in square millimeters where the metric system is employed.

Wire Gages. — The wire gage consists of a series of numbers used in practice as a means of identification of the various sizes of wires. The gage numbers are made intelligible by a table giving diameters of each size, weight per 1000 feet, feet per pound and, in the case of wires used as electrical conductors, resistance data per 1000 feet, etc.

In earlier years the gage numbers were used exclusively by manufacturers to indicate sizes, and different manufacturers adopted their own wire tables to accompany similar series of gage numbers. Thus the makers of steel wire had one gage and the makers of copper wire a different one. European gages were still different from those of American manufacturers.

Steel Wire Gage. — The Washburn and Moen gage was established in 1830 for use in the manufacture of iron and steel wire, and was later used by John A. Roebling & Sons for similar purposes. The American Steel and Wire Company, upon absorbing the Washburn & Moen Company, adopted its steel wire gage and gave it the name of the new company.

In 1912 the U. S. Bureau of Standards made a complete

study of wire gages, the results of which were published in its Bulletin 31. This report showed that the great majority of steel wire was being made in accordance with the American Steel and Wire gage and that this gage was quite well adapted to the purpose. It recommended this gage, therefore, as the "Steel Wire Gage" for the United States, and the American Institute of Electrical Engineers adopted this name as standard.

The other gages which are used to a limited extent are the Birmingham (sometimes called the Stubs Wire Gage), the Old English and the Stubs Steel Wire.

The Birmingham gage is said to have been established in the 18th century and was based upon the drawing process. No. 0 was the rod from which wire drawing was started; No. 1 was the first reduction; No. 2 the second and so on. Its gradations are rather irregular, for this reason, in some parts of the scale.

The British government made certain changes in the Birmingham gage with a view to smoothing out these irregularities and adopted the revised gage as its "Standard Wire Gage" by which it is now known.

American Wire Gage. — The American Wire Gage is used exclusively in America for copper wires and other wires intended for use as electrical conductors. It was devised by J. R. Brown of the Brown and Sharpe Mfg. Co. in 1857, and was for many years referred to as the B. & S. gage. The American Institute of Electrical Engineers adopted this gage as standard under the name American Wire Gage and this is the term now used by the Brown and Sharpe Co. as well as other manufacturers of electrical conductor wires in designating their output.

This gage was scientifically conceived as it is based upon a simple mathematical formula, which gives regular gradations in size from largest to smallest, and meets all practical requirements well.

The sizes grow smaller in diameter as the numbers grow larger, thus following the wire drawing process in a general way.

The diameter of 4/0, which is the largest size, is .46 inch, and the diameter of No. 36 is .005 inch. The diameter of any wire in the series is 1.1229 times that of the next higher number of the wire gage. Every size is 2.005 times the diameter of the sixth size smaller.

Thus No. 0 has a diameter 1.1229 times that of No. 1 and 2.005 times that of No. 6. In areas the ratio of any size to the next smaller size is 1.261, and any size has twice the area of the third smaller size. The area of No. 0 is 1.261 times that of No. 1, and 2.005 times that of No. 3. The area of the second larger size is 1.59 times that of any particular size which may be known.

Thus if it is carried in mind that No. 10 has an area of 10,380 circular mils, and a diameter of .1019 inch, it is a comparatively simple calculation to determine the diameter or area of any larger size. It is also useful to remember that No. 0 has approximately 10 times the area of No. 10 and therefore $\frac{1}{10}$ the resistance.

It is also useful to remember that No. 5 weighs 100 lb. per 1000 feet, as the weight per 1000 feet of any other size may be readily found by the use of the ratios above given for the area of cross-section.

For instance, knowing that No. 10 has an area of 10,380 circular mils, what is the area of No. 3 wire? As the area doubles every third size larger, No. 7 is double No. 10, or 20,760 circular mils, and No. 4 is double No. 7, or 41,520 circular mils. No. 3 is $1.26 \times 41{,}520$ or 52,300 circular mils.

Or, if the area of a smaller wire is desired, the next size smaller than 10 is .80 of the area of No. 10, the second size is .63 and the third size is .5 of No. 10. Thus the area of No. 13

is .5 of 10,380, or 5190 circular mils and the area of No. 14 is $.8 \times 5190 = 4150$ circular mils.

In a similar way, the resistance per 1000 feet of any size may be determined approximately without reference to a table, if the resistance of one size is known. As resistances decrease with increasing area, the resistance of any wire is 1.26 that of the next larger size, or .80 that of the next smaller size. It is 1.59 times that of the second larger size or .63 that of the second smaller wire and so on.

The values of area, weight and resistance may be calculated from the following formulæ, if no values are available:

If N represents the gage number (No. 0 being $0.00 = -1$, $000 = -2$ and $0000 = -3$) the resistance per 1000 feet is

$$R = 10^{\frac{N-10}{10}}. \quad \text{Log}\,(10\,R) = \frac{N}{10}.$$

The weight per 1000 ft. bare is

$$W = 10^{\frac{25-N}{10}}. \quad \text{Log}\,W = \frac{25-N}{10}.$$

The area in circular mils is

$$M = 10^{\frac{50.2-N}{10}}. \quad \text{Log}\,M = \frac{50.2-N}{10}.$$

These formulæ may be readily utilized without access to a table of logarithms by resorting to the ordinary 10-inch slide rule.

For instance, if it is desired to know the resistance per 1000 feet of No. 2, or No. 4 wire, the wire numbers are inserted in the formula $\log\,(10\,R) = \frac{N}{10}$ and the procedure is as follows:

$$\log\,(10\,R) = \frac{2}{10}.$$

Setting the figure 2 on the evenly divided scale of the slide the value of $10\,R$ is read as 1.585 on the lower scale of the rule

at the opposite end of the slide. $R = \frac{1.585}{10} = .1585$ which is approximately the resistance per 1000 feet of No. 2 wire. In a similar way, setting the slide at 4, the resistance of No. 4 is seen to be .251 ohm per 1000 feet.

If the weight is desired for these sizes, $\log W = \frac{25 - N}{10}$ and $\log W = \frac{25 - 2}{10} = 2.3$ for No. 2. 2 is the logarithm of 100 and setting the slide at 3 on the evenly divided scale, we read 2 at the other end of the slide on the lower scale. Hence $W = 2 \times 100 = 200$ lbs. per 1000 feet. Proceeding in a similar manner for No. 4, $\frac{25 - 4}{10} = 2.1$ we read 126 on the lower scale, whence the weight of No. 4 per 1000 ft. is 126 lbs.

To ascertain circular mils, $\log M = \frac{50.2 - N}{10}$.

For No. 2, $\log M = \frac{50.2 - 2}{10} = 4.82$. 4 is the logarithm of 10,000, and setting the slide at 8.2 on the evenly divided scale, read 6.62 at the opposite end on the lower scale of the rule. Hence No. 2 has $10{,}000 \times 6.62 = 66{,}200$ cir. mils. Similarly for No. 4, $\log M = \frac{50.2 - 4}{10} = 4.62$.

Setting the slide at 6.2 read 4.17. $4.17 \times 10{,}000 = 41{,}700$ c.m.

Edison Gage. — In the development of Edison low-tension mains, and feeders, it soon developed that sizes larger than the largest gage numbers would be very common. Edison therefore established a system of designating conductors by the number of thousands of circular mils of area. Thus a conductor having an area of 100,000 c.m. was called a 100 conductor. Similarly 500,000 c.m. was called 500 and 1,000,000 c.m. was called 1000.

This is perhaps not properly termed a wire gage, as it applies in most cases to stranded cables, made up of a considerable number of wires having numbers in the American Wire Gage. It, however, serves a very useful function in the designation of feeder and main sizes in low-tension networks.

The use of this system has had a tendency to encourage the use of areas of conductors as a means of designation rather than numbers and this limits the use of the wire gage numbers to smaller wires to a very large extent.

The diameter of wires of sizes down to No. 12 in the Roebling, Washburn & Moen, Birmingham, and American Wire gages are given in Table XVI.

TABLE XVI. — COMPARISON OF WIRE GAGES.

No.	Roebling, W. & Moen.	American.	Stubs Birmingham.
6–0	.460	....	....
5–0	.430	....	....
4–0	.393	.460	.454
3–0	.362	.4096	.425
2–0	.331	.3648	380
0	.307	.3249	.340
1	.283	.2893	.300
2	.263	.2576	.284
3	.244	.2294	.259
4	.225	.2043	.238
5	.207	.1819	.220
6	.192	.1620	.203
7	.177	.1443	.180
8	.162	.1285	.165
9	.148	.1144	.148
10	.135	.1019	.134
11	.120	.0907	.120
12	.105	.0808	.109

Stranded Cables. — In the larger sizes of conductors the rigidity of a single wire is so great that it is necessary that it be subdivided into a number of strands sufficient to give the necessary flexibility for handling economically.

The strands may be arranged in concentric layers about a

central core, or they may consist of a "rope-lay" made up by combining several smaller cables having a concentric lay as shown in Fig. 176. The rope lay is not used generally for electrical conductors, its use being limited to extra flexible cables having very small wires.

In a concentric lay cable the smallest number of wires which is used is seven. The space about the core is filled by six

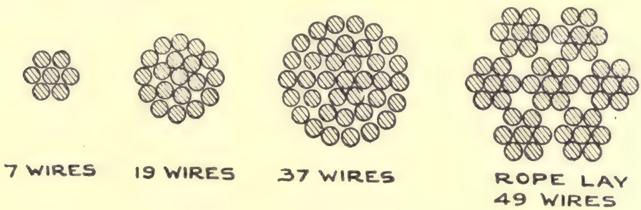


Fig. 176. Cable Stranding.

conductors since the diameter of the circle passing through their centers is twice the diameter of the wire and the circumference of the circle is 6 d. Likewise the diameter of the third layer is 4 d and 12 conductors fill the space making a 19-conductor cable.

The other formations follow the same rule as shown in Table XX. The stranding practice for various sizes is also given therein.

The diameter of a concentric lay cable is taken as that of the circle circumscribing the outer layer. It is expressed approximately by the formula $D = d\ (2\ n + 1)$ in which d is the diameter of the individual conductors and n is the number of layers on the core. Therefore a 19-strand 2-layer cable of wires, having a diameter of .1 inch, the outside diameter is $D = .1\ (2 \times 2 + 1) = .5$ inch. The diameter is about 15 per cent greater than that of a solid wire of equal cross-section.

The pitch of a cable is the ratio of the axial length of one complete turn of a strand to the diameter of the cable. This

varies somewhat with different manufacturers and with the size of the cable. It is made as high as practical, however, as a low pitch requires a greater length of strand to produce a given length of cable. In cables having a pitch of 15.7 the resistance is increased 2 per cent over what it would be if there were no spiraling. The weight is increased by a like percentage also. For a cable having a pitch materially different from the value 15.7 the resistance and weight may be calculated by applying the following correction factor to the values given in the table for stranded cables. The correction factor is

$$1 + .01\left(\frac{493}{P^2} - 2\right).$$

Then if the pitch is 12 the factor is $1 + .01\left(\frac{493}{144} - 2\right) = 1.0142$,

or if the pitch is 20 the factor is $1 + .01\left(\frac{493}{400} - 2\right) = .9926$.

The diameter of the strands of a cable must usually be drawn to a special size in order to make them aggregate the total cross-section. Thus a 7-conductor cable of No. 2 A.W.G. which is to have an equivalent area of 66,400 circular mils must be made up of $66{,}400 \times 1.02 = 67{,}700$ circular mils. Each of the seven strands must therefore have an area of 9670 circular mils, which is a little less than No. 10 but more than No. 9.

The data for stranded cables appears in Table XX.

Resistance and Conductivity. — The resistance of a conductor to the flow of electrical energy depends: (*a*) upon the metal of which it is made; (*b*) upon the method of manufacture and purity of the metal; and (*c*) upon the temperature at which it carries the electric current.

The various metals which are present in sufficient quantity

to be available for use as conductors have resistances which differ very widely. The metals silver, copper, gold and aluminum are the best conductors in the order named. Silver is 8 per cent better as a conductor than copper, while copper is about 40 per cent better than gold or aluminum. The method of manufacture of a metal has a considerable influence upon its resistance. Copper in the form of castings ordinarily contains so much impurity that its resistance is from 25 per cent to 100 per cent higher than copper, which has been drawn or rolled after refining. The resistance of drawn copper is somewhat affected by annealing after the drawing process, the resistance being slightly reduced by annealing.

The resistance of all metallic conductors varies with the temperature, being increased by an increase in temperature. Carbon affords a notable contrast to metallic conductors in that its resistance decreases with increasing temperature. Conductivity is the reciprocal of resistance, that is, the conductivity of a conductor is $\frac{1}{R}$, R being its resistance.

For purposes of comparison of conductors, conductivity affords a more convenient working basis than resistance, since the higher the conductivity, the better the conductor for purposes of distribution. Copper, being the most common metal in use for conducting purposes, is made the basis of comparison, and is said to have 100 per cent conductivity when its purity and density are such that one foot of copper wire having a diameter of 1 mil (.001 inch) has a resistance of 10.371 ohms at a temperature of 20 degrees C. or 68 degrees F.

Ordinary commercial drawn or rolled copper has a conductivity of 96 per cent to 99.5 per cent of this value and occasionally samples are found having a conductivity of over 100 per cent. It is usual to specify a conductivity of about 98 per cent when selecting cables for heavy currents and important service.

Table XVII shows the conductivity, resistance and temperature coefficients of various common metals.

TABLE XVII. — RESISTANCE AND CONDUCTIVITY OF VARIOUS METALS.

	Per cent conductivity.	Resistivity at 20° C., ohms mil-ft.	Temp. coefficient from 20° C. per deg. C.	Temp. coefficient from 32° F. per deg. F.
Silver	108.2	9.53	.00370	.00222
Annealed copper	100	10.37	.00393	.00240
Gold	72.5	14.21	.00350	.00210
Aluminum	62.1	16.66	.00389	.00235
Zinc	27.6	37.34	.00375	.00226
Platinum (annealed)	17.7	56.60	.00236	.00137
Iron	17.6	61.32	.00555	.00347
Nickel	12.9	84.63	.00553	.00345
Tin	12.1	85.62	.00404	.00245
Lead	7.82	125.54	.00380	.00228

Resistivity. — The resistivity of a metal is the resistance of a certain mass of the metal having certain arbitrarily chosen dimensions. Thus it may be expressed as the resistance between two faces of a cubic centimeter of the metal, or of a wire having a diameter of one mil and a length of one foot, or of a wire having a length of one meter and a weight of one gram. These quantities, when fixed for the pure metal, constitute a standard of reference to which any sample of commercial wire may be directly compared by making resistance measurements and reducing them to the equivalent of these standards.

Resistivity is also known as specific resistance, but this term is not a true expression of the character of the quantity and the term is not approved by the best authorities.

Resistivity is usually expressed directly in ohms, while conductivity is more often expressed as a percentage of the annealed copper standard. The resistivity of pure annealed copper at 20 degrees C. or 68 degrees F. is 10.371 ohms per foot of wire, 1 mil in diameter, or .15328 ohms per meter of wire weighing one gram or 31.394 ohms per 1000 feet of a wire

weighing one pound per 1000 feet. This was adopted as the Annealed Copper Standard by the International Electrotechnical Commission in 1913 and is used as the basis of reference for copper and other conductors where resistivity or conductivity is a factor.

In making measurements of resistivity of commercial samples it is possible to make a more accurate determination by the use of the ohms per meter-gram or per mile pound as a standard than by the ohms per mil-foot, since weights may be more accurately determined than diameters in most cases. The resistivity as determined from ohms per meter-gram is termed mass-resistivity, while that derived on the basis of circular mils is known as volume resistivity.

Mass resistivity $= \frac{RW}{L^2}$, in which R is the resistance of the sample, W is its weight and L is its length.

If a length of ten meters of a wire measures .084 ohm and it weighs 185 grams, its resistivity is $\frac{.084 \times 185}{10 \times 10} = .15540$ ohm per meter-gram.

The conductivity of this sample as compared with the annealed copper standard of .15328 ohm (meter-gram) is therefore

$$\frac{.15328}{.15540} = 98.63 \text{ per cent.}$$

The volume resistivity of a wire is $\frac{Rs}{L}$ in which s is the area of cross-section in circular mils.

If a wire having a length $L = 10$ feet, and a cross-section s of 4110 circular mils is found to have a resistance of .0257 ohm at 20 degrees $C.$, its resistivity is

$$\frac{.0257 \times 4110}{10} = 10.512 \text{ ohms (mil-foot).}$$

The conductivity of the sample as compared with the annealed copper standard of 10.371 ohms (mil-foot) is therefore

$$\frac{10.371}{10.512} = 98.65 \text{ per cent.}$$

Copper. — The commercial distribution of electricity is largely dependent upon the existence of a metal of low resistance to the passage of electricity, high resistance to the corrosive action of moisture in the atmosphere and existing in such quantities as to permit investments to be made in conductors which are within economical limits. Such a metal is copper. It has a density of 8.9 grams per cubic centimeter or 555 lbs. per cubic foot. It melts at 1081 degrees C. or 1981 degrees F. and boils at 2310 degrees C. or 4190 degrees F., giving off a greenish flame. In the molten state it readily absorbs oxygen, hydrogen, carbon dioxide, or carbon monoxide, and when the cooling metal drives off these gases, these are likely to be occluded, thus forming so-called blow holes in the finished casting.

The electrical conductivity of the metal varies widely according to the impurities contained in it. It is therefore classified for commercial purposes into three grades known as electrolytic, lake and casting copper. The first is the product of refinement of casting copper by electrolytic processes and is about 99.9 per cent pure. Lake copper is made by melting nuggets of the native metal into bars. Casting copper is that derived from smelting the ores and necessarily contains considerable impurities. It is used chiefly for mechanical purposes. This grade of copper is also derived from impure solutions electrolytically and from processes yielding copper as a by-product. The better grades of casting copper are about 99 per cent pure.

Lake copper is mined in the northern peninsula of Michigan in a rock ore which is crushed in stamp mills, concentrated

and melted into bars. This is the only source of this kind of copper.

Temperature Coefficient. -- The variation of resistance of a conductor with rise or fall of temperature follows a definite law for any given metal which may be expressed in the form

$$Rt = R_{t_1}\,[1 + a_{t_1}\,(t - t_1)],$$

in which R_{t_1} is the known resistance at t_1 degrees C.

a_{t_1} is a constant for the rate of increase when starting at t_1 degrees C., t is the temperature at which it is desired to know the value of R_t. Thus if it is known that a conductor has a certain resistance at a temperature of 20 degrees C. its resistance at 50 degrees C. may be readily determined by this rule if the values of a_t have been experimentally established for various temperatures within usual working limits.

The value of a_t, the temperature coefficient, varies with the temperature at the starting point. It is higher for resistances measured initially at 0 degree, than for those measured at 20 or 30 degrees. It also varies with the conductivity of the metal, as shown in Table XVIII.

TABLE XVIII.—TEMPERATURE COEFFICIENTS OF COPPER FOR DIFFERENT INITIAL TEMPERATURES (CENTIGRADE) AND DIFFERENT CONDUCTIVITIES.

Per cent conductivity.	a_0	a_{15}	a_{20}	a_{25}	a_{30}	a_{50}
95	.00403	.00380	.00373	.00367	.00360	.00336
96	.00408	.00385	.00377	.00370	.00364	.00339
97	.00413	.00389	.00381	.00374	.00367	.00342
97.3	.00414	.00390	.00382	.00375	.00368	.00343
98	.00417	.00393	.00385	.00378	.00371	.00345
99	.00422	.00397	.00389	.00382	.00374	.00348
100	.00427	.00401	.00393	.00385	.00378	.00352
101	.00431	.00405	.00397	.00389	.00382	.00355

In the case of annealed copper the values of a_t have been determined with great care by investigators of this country and Europe and the figures appearing in the above table are

the standard values as published by the U. S. Bureau of Standards.

The values given for a conductivity of 100 per cent may be used for annealed copper in the form of so-called "soft drawn" wire, or the windings of transformers and electrical machinery.

Hard drawn wire has an average conductivity of 97.3 per cent and the values given for that conductivity in the table should be used for such wire.

With an annealed copper conductor having a resistance of .2 ohm at 20 degrees C. the resistance at 45 degrees C. would be

$$R = .2\,[1 + .00393\,(45 - 20)] = .2(1.0982) = .2196 \text{ ohm.}$$

With hard copper having a resistance of .2 ohm for a certain length at 20 degrees C. the resistance at 45 degrees C. is

$$R = .2\,[1 + .00382\,(45 - 20)] = .2(1.0955) = .2191 \text{ ohm.}$$

The average temperature of a cable or transformer coil may be calculated from measurements of its resistance at normal temperature and again after it has had its temperature increased by the passage of current by the use of the foregoing formula.

For example, a cable was found to measure .5 ohm with average manhole temperatures of 15 degrees C. (59 degrees F.) and .55 ohm after a 6-hour run under load. What was its average temperature at the end of the run?

In the formula, $R = .55$, $R_t = .5$ and a_t is .00393.

Whence,

$$.55 = .5\,[1 + .00401\,(t - 15)] = .5 + .002005\,(t - 15),$$

$$\frac{.55 - .5}{.002005} = t - 15,$$

$$t = \frac{.05}{.002005} + 15 = 40 \text{ degrees C.}$$

Again, if a coil has a resistance of 10 ohms at 20 degrees C.

(68 degrees F.) and a resistance of 11.5 ohms after carrying a load, what is its temperature?

$$11.5 = 10\,[1 + .00393\,(t - 20)] = 10 + .0393\,(t - 20),$$

$$\frac{11.5 - 10}{.0393} + 20 = t = 58.1 \text{ degrees C.}$$

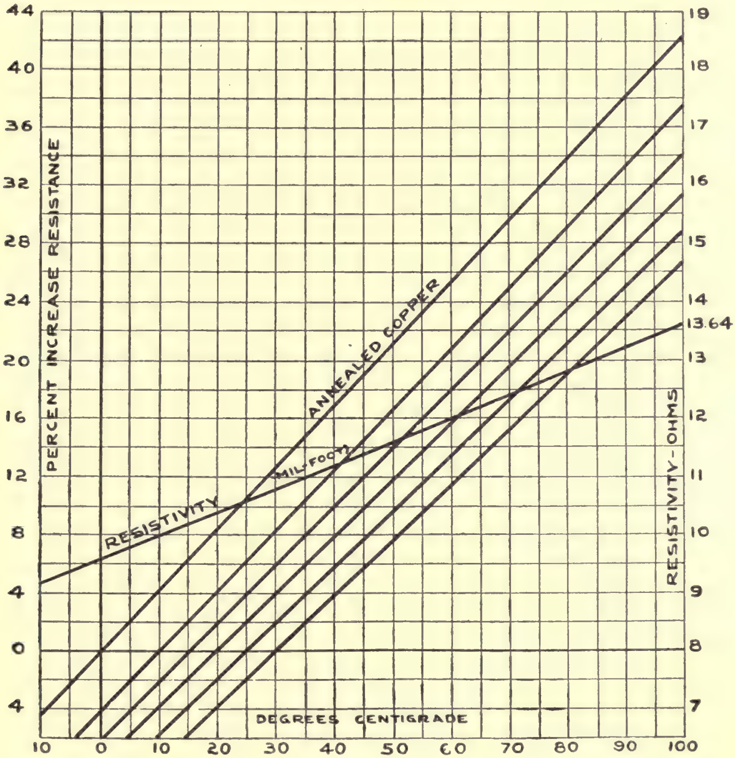


Fig. 177.

Calculations of resistances at various temperatures or of temperatures corresponding to different resistances may be facilitated by the use of a diagram such as that in Fig. 177, which shows the percentage of increase of resistance at all temperatures up to 100 degrees C. from 0, 10, 15, 20, 25 and

30 degrees points of reference, for annealed copper. It also shows the change in resistivity (mil-foot) as the temperature varies.

Referring to the foregoing cases which were calculated by the use of the formula, the solutions are made by the use of the diagram as follows:

Given a conductor with a resistance of .2 ohm at 20 degrees C., what is its resistance at 45 degrees C.?

Referring to the diagram, the line crossing the line of 0 percentage at 20 degrees crosses the 45 degree line at 9.8 per

TABLE XIX.—PROPERTIES OF ANNEALED COPPER WIRE.

Size, A.W.G.	Diameter in mils.	Cross-section.		Weight per 1000 ft.	Per 1000 ft. weather-proof.	Ohms per 1000 ft.	
		Circular mils.	Square mils.			20° C.	50° C.
0000	460.0	211,600	.1662	640.5	741	.04901	.05482
000	409.6	167,800	.1318	570.9	598	.06180	.06912
00	364.8	133,100	.1045	402.8	485	.07783	.08716
0	324.9	105,500	.08289	319.5	382	.1002	.1099
1	289.3	83,690	.06573	253.3	312	.1264	.1386
2	257.6	66,370	.06213	200.9	254	.1563	.1748
3	229.4	52,640	.04134	159.3	199	.1970	.2204
4	204.3	41,740	.03278	126.4	163	.2485	.2779
5	181.9	33,100	.02600	100.2	132	.3133	.3504
6	162.0	26,250	.02062	79.46	109	.3951	.4418
7	144.3	20,820	.01635	63.02	88	.4982	.5572
8	128.5	16,510	.01297	49.98	74	.6282	.7025
9	114.4	13,090	.01028	39.63	60	.7921	.8860
10	101.9	10,380	.008155	31.43	50	.9989	1.117
11	90.74	8,234	.006467	24.92	42	1.260	1.409
12	80.81	6,530	.005129	19.77	34	1.588	1.776
13	71.96	5,178	.004067	15.68	......	2.003	2.240
14	64.08	4,107	.003225	12.43	24	2.525	2.824
15	57.07	3,257	.002558	9.858	......	3.184	3.562
16	50.82	2,583	.002028	7.818	19	4.015	4.491

cent. Hence the increase in resistance is 9.8 per cent and the resistance of the conductor at 45 degrees is $1.098 \times .2 = .2196$ ohm, as found by calculation.

Given a cable having a resistance of .5 ohm at 15 degrees and of .55 ohm after a run under load, what is its average temperature?

The increase in resistance is .05 ohm or 10 per cent. Following the line which crosses the 0 line at 15 degrees until it reaches 10 per cent the temperature is seen to be 40 degrees, as found by calculation.

In a similar way for any ordinary initial temperature resistances may be determined by following the line which crosses the zero line at the initial temperature in question.

The diagram may be used for aluminum as well as copper as the temperature coefficients of these two metals are very nearly equal.

TABLE XX. — PROPERTIES OF ANNEALED STRANDED COPPER CABLES.

Size, A.W.G.	Circular mils.	Weight per 1000 ft.	Standard strands.			Ohms per 1000 ft.	
			Number of wires.	Diameter of wires in mils.	Outside diameter in mils.	25° C.	65° C.
....	2,000,000	6,180	127	125.5	1631	.00539	.00623
....	1,500,000	4,630	91	128.4	1412	.00719	.00839
....	1,000,000	3,090	61	128.0	1152	.0108	.0125
....	750,000	2,320	61	110.9	998	.0144	.0166
....	600,000	1,850	61	99.2	893	.0180	.0208
....	500,000	1,540	37	116.2	814	.0216	.0249
....	400,000	1,240	37	104.0	728	.0270	.0311
....	350,000	1,080	37	97.3	681	.0308	.0356
....	300,000	926	37	90.0	630	.0360	.0415
....	250,000	772	37	82.2	575	.0432	.0498
0000	....	653	19	105.5	528	.0510	.0589
000	....	518	19	94.0	470	.0643	.0742
00	....	411	19	83.7	418	.0811	.0936
0	....	326	19	74.5	373	.102	.118
1	....	258	19	66.4	332	.129	.149
2	....	205	7	97.4	292	.163	.188
3	....	163	7	86.7	260	.205	.237
4	....	129	7	77.2	232	.258	.298
5	....	102	7	68.8	206	.326	.376
6	....	81	7	61.2	184	.411	.475

With a diagram drawn to a larger scale quite accurate results can be secured graphically with a minimum of calculation.

The size, weight and resistance of the sizes of solid wire in general use in distribution are given in Table No. XIX

and similar data for stranded cables up to 2,000,000 circular mils in Table No. XX.

Mechanical Properties of Copper. — The tensile strength of copper varies with its physical condition. In the form of annealed wire it breaks at 32,000 to 37,000 pounds per square inch in the larger sizes and at 35,000 to 40,000 pounds in the smaller sizes. Hard drawn wire has a strength of about 50,000 pounds per square inch in the large sizes and 65,000 pounds per square inch in the smaller sizes. Cast copper ranges from 20,000 to 30,000 per square inch.

The strength of hard drawn wire is reduced to that of annealed wire by subjecting it to a temperature of about 250 degrees C. The strength reduction proceeds rapidly between 150 degrees and 225 degrees C. For this reason the soldering of joints reduces the strength of the wire near the joint to that of annealed wire. The use of a mechanical form of joint is therefore usual where hard drawn wires are spliced or tapped at points where they are under strain which is too great for annealed wire.

The process of cold drawing hardens the wire and the more it is reduced in section the harder it becomes. The smaller sizes are the stronger because a larger portion of the metal is in the hardened state.

Annealed copper is quite ductile and stretches appreciably under stresses which are considerably below its breaking point. It elongates about 35 per cent over its initial length before breaking. Hard drawn copper is, however, much less subject to elongation. In the larger sizes it takes a permanent set of about 4 per cent, but the smaller sizes are elongated only 1 to 2 per cent. The elongation of copper wires affords a material relief to overhead wires which are loaded with sleet and contracted by low temperatures, since the tensile strains are relieved by the elongation of the wire.

The elongation of concentric lay cables is somewhat greater than that of solid wires, since the stress tends to cause a re-adjustment of the pitch of the cable. The strength of such cables is probably not over 90 per cent of that of an equivalent solid conductor.

The elongation of wires was discussed in a paper by F. O. Blackwell, read before the International Electrotechnical

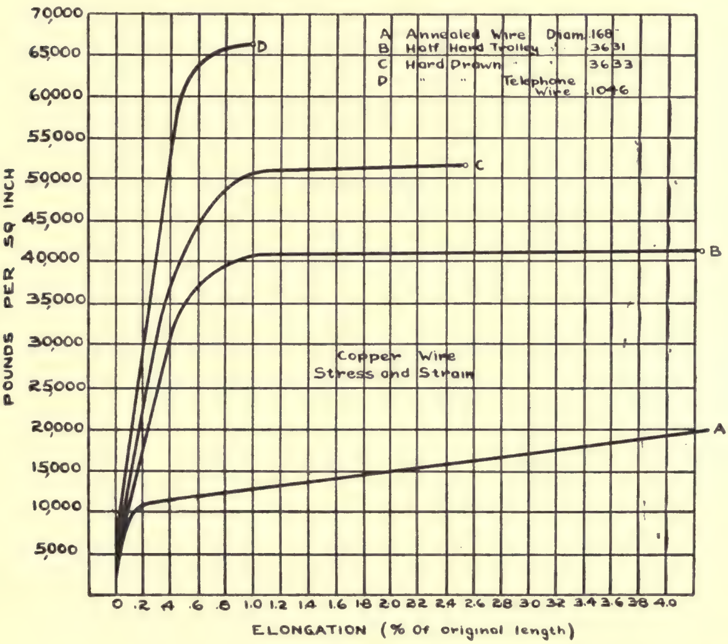


Fig. 178.

Congress in 1904. The experiments therein described showed that copper wire stretches gradually when kept under strains which are considerably below the elastic limit. When the stress is removed and reapplied the wire behaves as if it had been hardened by stretching. It requires a greater stress to produce a given elongation and the elastic limit is increased.

The curves in Fig. 178 show the manner in which copper

wire in various conditions of hardness elongates under stress. Curve A shows that annealed wire .168 inch in diameter begins to elongate rapidly under a load of 10,000 lbs. per square inch. Medium hard drawn trolley wire begins to stretch rapidly between 35,000 and 40,000 lbs. per square inch, while a No. 10 hard drawn telephone wire does not stretch until 60,000 lbs. per square inch has been exceeded.

In the case of annealed wire the stretching process is slow enough to permit additional strain to be applied. The limits of the curve are much too small to carry this out to the breaking point, as it does not break until an elongation of about 35 per cent has been reached. With hard drawn wire the elongation proceeds too rapidly after the elastic limit has been passed to permit much increase in the stress to be made.

It is evident from these curves that the elastic limit of copper is not a definite quantity, but varies with the degree of hardness of the metal and to some extent with the rate at which the application of load is increased. It is usually considered that loads applied in overhead construction should not exceed 50 per cent of the ultimate breaking strength, under the most severe conditions of loading.

The breaking strengths of wires of No. 10 to 0000 as required by the specifications of the American Society for Testing Materials appear in the table on the following page.

Aluminum. — The use of aluminum in transmission practice has been sufficiently general to make its properties of importance to electrical engineers. It has the very low density of 2.7 grains per cubic centimeter, as compared with 8.9 for copper, and this is the principal reason for its use. It is ductile and may be hard drawn and treated otherwise much the same as copper.

Aluminum melts at 658 degrees C. and boils at 1800 degrees C. Like copper it is protected by the thin coating of

STRENGTH OF COPPER WIRES.

Gage No., A.W.G.	Diameter in mils.	Breaking load (lbs. per sq. in.)		
		Annealed.	Medium.	Hard.
0000	460	5,650	6,980	8,310
000	410	4,480	5,680	6,590
00	365	3,560	4,620	5,220
0	325	2,820	3,730	4,560
1	289	2,240	3,020	3,740
2	258	1,870	2,450	3,120
3	229	1,400	1,980	2,480
4	204	1,115	1,590	1,960
5	182	885	1,260	1,560
6	162	700	1,010	1,240
8	128	60	646	790
10	102	00	410	490

oxide which forms upon it and prevents further corrosion under atmospheric conditions. This protective coating forms so quickly and is so refractory that it is not possible to solder aluminum in the ordinary manner. Its electrical conductivity is affected by its purity as is copper, and it has a somewhat lower conductivity when hard drawn than in the annealed state. The impurities are usually silicon and iron.

The mass resistivity of aluminum is .0764 ohm (meter-gram) at 20 degrees C. The conductivity is 61 per cent of annealed copper, and the density being $\frac{2.7}{8.9} = 30.33$ per cent of copper, it follows that an aluminum conductor having the same resistance per 1000 feet as a copper conductor has a weight of $\frac{30.33}{61} = .497$ of the copper conductor.

The temperature coefficient varies as it does with copper according to the temperature of reference, but it has an average value of .0039 per degree C. from and at 20 degrees C.

The size, weight and resistance of aluminum wires appears in Table XXI.

TABLE XXI.—PROPERTIES OF STRANDED ALUMINUM CABLES.

No. B. & S.	Bare diam., mils.	Area, circular mils.	Weight.				Resistance at 68 deg. F.	
			Per 1000 ft.	Per mile.	Per 1000 ft., weatherproof.	Bare feet per lb.	Per 1000 ft.	Per mile.
......	1.15	1,000,000	920	4,858	1,408	1.087	.01695	.0895
......	1.00	750,000	690	3,645	1,067	1.45	.0226	.1193
......	.81	500,000	460	2,430	740	2.04	.033	.179
......	.73	400,000	368	1,944	567	2.72	.0424	.224
......	.68	350,000	322	1,701	502	3.11	.0484	.256
......	.63	300,000	276	1,458	436	3.62	.0565	.298
......	.58	250,000	230	1,215	375	4.35	.0678	.358
4-0	.54	211,600	195	1,028	280	5.73	.08	.423
3-0	.47	167,800	154	816	232	6.48	.101	.533
2-0	.42	133,100	122	647	192	8.16	.127	.673
0	.37	105,500	97.1	513	155	10.3	.160	.847
1	.33	83,690	77	407	132	13	.202	1.069
2	.30	66,270	61	323	108	16.4	.255	1.35
3	.26	52,630	48.5	256	88	20.6	.322	1.70
4	.23	41,740	38.5	203	72	26	.406	2.141

The tensile strength varies with the hardness and method of treatment during manufacture. Castings have a strength under tension of 12,000 to 14,000 pounds per square inch. Soft wire has a strength of 14,000 pounds per square inch in the larger sizes of wire and as high as 33,000 pounds per square inch in the small sizes. Hard drawn wire in sizes ordinarily used in overhead lines has a strength of 23,000 to 27,000 pounds per square inch. This is used for overhead lines exclusively. The coefficient of expansion with variation of temperature is approximately .0000231 per degrees C. at temperatures between 0 and 100 degrees C.

The elongation of aluminum under the stress of overhead construction is more uniform than that of copper, it being appreciable at loads considerably below the safe working stress of 50 per cent of the ultimate breaking strength. The rate of elongation is shown very well in the diagram, Fig. 179, for a No. 6 A.W.G. conductor. In hard drawn wires the total elongation at rupture is from 2 to 4 per cent.

Copper Clad Steel. — Steel wire with copper coating has certain advantages for use where great strength is required without a high conductivity. This wire is made up in rods

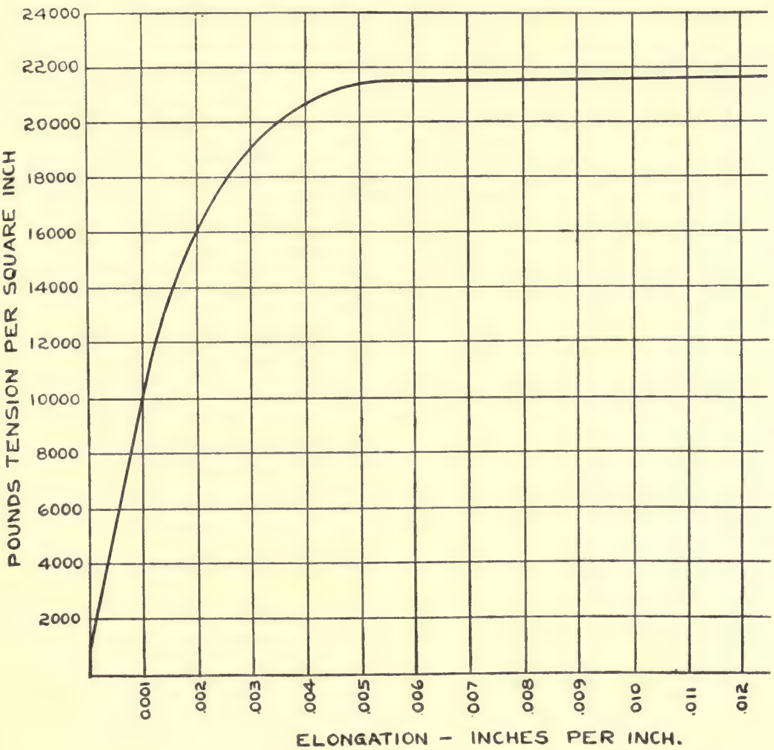


Fig. 179. Aluminum.

with the proper proportion of steel and copper and then drawn into wire, having an electrical conductivity of 30 to 50 per cent of that of a copper wire of equal cross-section. The wire is annealed at intervals between successive reductions and may be had as soft, medium or hard wire.

The temperature coefficient is approximately .0045 per degree C. from and at 0 C.

The coefficient of linear expansion is .0000129 per degree C. and the density is 8.2 grams per cu. cm.

The tensile strength depends somewhat upon the steel forming the core, but usually varies from 80,000 to 100,000 pounds per square inch. The elongation is very similar to that of hard drawn copper.

Steel Wire and Cables. — The use of steel wire and cable for electrical distribution is general where great strength is required and where low first cost to reach a small neighboring community is necessary. It is also used in great quantities for guying and cable suspension purposes.

The resistivity of iron and steel varies widely with their composition. In general it is about six times that of copper for wrought iron and about eight times that of copper for steel.

The temperature coefficient of resistance of pure iron has a mean value of about .000635 per degree C. between 0 and 100 degrees C. In the form of carbon steel this varies from .00025 to .00042, depending upon the temper. The former figure applies to a light yellow temper, and the latter to soft dark blue steel.

The density of iron is 7.86 grams per cubic centimeter and that of steel about 2 per cent greater. Iron weighs 480 pounds per cubic foot and steel about 490 pounds.

The tensile strength depends upon composition as well as upon the process of manufacture. It varies from 50,000 pounds per square inch for soft pure iron to 180,000 pounds or more in hard drawn steel wire.

The elongation before rupture is about 10 per cent for iron wire and elastic limit is reached at about 50 per cent of the breaking point. The coefficient of linear expansion is about .0000064 per degree F.

Steel wire is used largely in the form of stranded cable for guying purposes, or as ground wire on transmission lines,

seven-strand cable being usual. In the case of branch lines from high voltage systems supplying a small load small single conductor wire is often employed, as the current is small and the investment must be kept as low as possible.

Current Carrying Capacity. — The flow of electricity along a conductor is accompanied by a loss of energy which is proportional to the square of the current in amperes and the resistance of the circuit. This may be written watts loss = C^2R, C being the current flowing and R the resistance of the circuit. The loss in a circuit having a resistance of .1 ohm when it is carrying a load of 100 amperes is 100 × 100 × .1 = 1000 watts. The energy absorbed by the resistance of the circuit is dissipated in the form of heat, which raises the temperature of the conductor in proportion to the energy absorbed and to the heat radiated. The maximum current carrying capacity of a conductor of given size is therefore

TABLE XXII. — CURRENT CARRYING CAPACITY OF COPPER CONDUCTORS.

Size, A.W.G.	Rubber.	Weatherproof.	Size, A.W.G.	Rubber.	Weatherproof.
14	15	20	00	150	225
12	20	25	000	175	275
10	25	30	0000	225	325
8	35	50	250,000	235	350
6	50	70	300,000	275	400
5	55	80	350,000	300	450
4	70	90	400,000	325	500
3	80	100	500,000	400	600
2	90	125	750,000	525	800
1	100	150	1,000,000	650	1,000
0	125	200	1,500,000	850	1,360
....	....	....	2,000,000	1,050	1,670

dependent upon whether it is installed in open air, in conduit or underground. The character of the insulation is also a factor, since certain insulations may be safely operated at higher temperatures than others. Weatherproof insulation

may be safely operated at higher temperatures than rubber, while bare wire may be operated at much higher temperatures than any of the usual forms of insulation will withstand.

If the maximum allowable temperature is known for any class of insulation the maximum current which the circuit may carry under the given condition may be calculated from the following formula:

$C = A\sqrt{\frac{TD^3}{1.8\,r}}$, in which T is the rise in temperature in degrees F., D is the diameter of the conductor in inches (not including insulation), r is the resistance per mil-foot at the final temperature, and A is a constant which varies with the character of the insulation and method of installation as follows:

Bare wire in open air	A is 1100
Bare wire indoors	A is 600
Rubber-covered wire indoors	A is 500
Underground cable, rubber insulation, single conductor	A is 500
Underground cable, paper or cloth, single conductor	A is 550
Underground cable, rubber insulation, three conductor	A is 380
Underground cable, paper or cloth, three conductor	A is 330

The values of r, the resistivity, at various temperatures, are shown in the curve in Fig. 176.

With a circuit of No. 0 bare copper wire in open air, in which it is permissible to allow the temperature to rise from 70 to 120 degrees F., D is .325, T is 50, r is 11.6 and A is 1100. The current which would produce this rise in temperature is

$C = 1100\sqrt{\frac{50 \times (.325)^3}{1.8 \times 11.6}} = 310$ amperes. The same wire in-

doors could be loaded to $\frac{600}{1100} \times 310 = 170$ amperes, or in an underground single-conductor paper cable to $\frac{550}{1100} \times 310 = 155$ amperes.

The use of such a formula is of value chiefly for special cases, as it is more convenient to have tables showing the current carrying capacity of the various sizes of conductors under different conditions for ordinary use.

The safe carrying capacity of the sizes of conductors commonly used in distribution work is given in Table XXII. These are the values permitted by the National Electric Code in interior work and they may be exceeded somewhat in outdoor or underground construction.

Voltage Drop. — The transmission of electricity over a conductor is accompanied by a loss of pressure due to its resistance. The scientist Ohm discovered that this loss was $E = C \times R$, when C is the current flowing and R the resistance of the conductor, and it is called Ohm's law. It is strictly true only for direct-current circuits.

A simple electric circuit is composed of two elements, the conductors leading to the lamp or motor and the receiving device itself. The current passing through the circuit is the same in both elements, but the resistances of the conductors and the lamp are different, and the fall of pressure as the current passes on its way through the circuit is directly proportional to these resistances.

The function of the conductor being to convey the supply of electricity from its source to the consuming device, it is desirable that as little pressure be absorbed by the resistance of the conductor as possible.

Calculation of Direct Current Circuits. — The problem of designing a circuit is therefore one of determining what size

of conductor should be used to limit the loss of voltage to a specified amount, when the distance and current to be carried are known.

The resistance of a mil-foot of copper at 68 degrees F. being about 10.4 ohms, that of a conductor D feet long and M circular mils in area is $R = \frac{D \times 10.4}{M}$. The drop with current C is therefore $E = CR = \frac{C \times D \times 10.4}{M}$ or $M = \frac{C \times D \times 10.4}{E}$. If both conductors are of the same size the total drop is $E = \frac{2\,D \times C \times 10.4}{M}$. If they are not of the same size, the drop in the different sizes must be figured separately and added together.

For example, assume that a two-wire circuit is to carry a load of 100 amperes at a distance of 300 feet with a drop of five volts, what size of conductor must be used?

$$M = \frac{2\,D \times C \times 10.4}{E} = \frac{2 \times 300 \times 100 \times 10.4}{5} = 124{,}800 \text{ c.m.},$$

which is found by reference to Table XIX to be approximately the section of No. 00, which should be used.

If a circuit of No. 4/0 wire is to carry 100 amperes 500 feet, what will be the voltage drop? In Table XIX No. 4/0 has an area of 211,600 circular mils, and $E = \frac{2 \times 500 \times 100 \times 10.4}{211{,}600} = 4.9$ volts.

The calculation of such problems can be simplified where the size of the circuit is already fixed by the use of the values of resistance per 1000 feet given in Table XIX. For instance, in the case of the 500-foot circuit of No. 4/0 wire, the resistance per 1000 feet being .0489 ohm, and the circuit being .5 thousand feet long, $E = C \times R = 100 \times .0489 \times .5 \times 2 = 4.9$ volts. This operation involves only multiplication, and the calculation is therefore somewhat more simple.

The use of a table is not always convenient, but when this method is used regularly, it becomes an easy matter to memorize the resistance of a few principal sizes, from which it is easy to find the odd sizes by applying the law of the American wire gauge table, as hereinbefore described.

Three-wire Circuits. — In making calculations for a three-wire Edison circuit, separate computations must be made for each conductor if the load is appreciably unbalanced.

For example, if a circuit having two 4/0 outers and a No. 0 neutral 1000 feet long carries a load of 150 amperes on the positive side and 110 on the negative, the drop will be found as follows:

Resistance of 1000 feet of 4/0 = .05 ohm and that of No. 0 = .1 ohm.

$$E = CR = 150 \times 0.5 = 7.5 \text{ volts on positive wire.}$$
$$E = CR = 110 \times .05 = 5.5 \text{ volts on negative wire.}$$
$$E = CR = 40 \times .1 = 4 \text{ volts on neutral wire.}$$

The neutral wire drop is added to the drop on the heavy side and subtracted from that on the lighter side, making the drop $7.5 + 4 = 11.5$ volts on the heavy side and $5.5 - 4 = 1.5$ volts on the other side. If the pressure of the supply is 120 volts on each side, the pressure at the other end will be 120 less 11.5 = 108.5 on the positive side, and 120 less 1.5 = 118.5 on the negative side. These relations are shown graphically in Fig. 180 (*a*).

This example illustrates the importance of keeping three-wire mains approximately balanced. It also indicates the necessity of having the neutral of ample size so as not to emphasize unbalanced conditions when they exist. In this case, if the neutral had been of 4/0 the drop on it would have been 2 volts; the pressure on the positive side at the far end would have been 110.5 volts, with 116.5 on the negative.

When the conditions are such that the drop on the neutral conductor exceeds that on the lighter loaded side, the pressure on the lighter side at the far end is higher than the pressure at the source of supply. This condition is illustrated in Fig. 180 (*b*), and is one which is sometimes found in practice

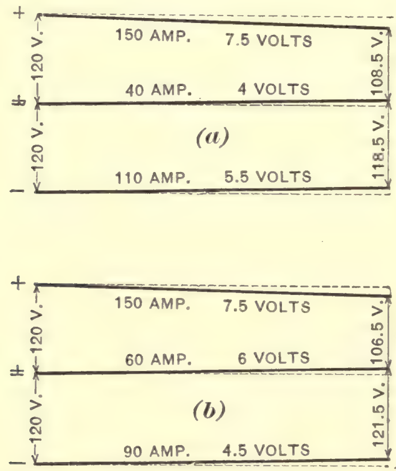


Fig. 180. Voltage Drop in Three-wire Circuit.

on branches where the load consists of a few two-wire consumers whose hours of use are so irregular that they cannot be arranged to balance each other at all times.

In this case the outsides are 4/0 and the neutral No. 0.

The drop on the positive at 150 amperes is 7.5 volts.

The drop on the negative at 90 amperes is 4.5 volts.

The drop on the neutral at 60 amperes is 6 volts.

With 120 volts at the point of supply the pressure at the far end is 120 less $(7.5 + 6)$ volts $= 106.5$ volts on the positive side, while on the negative side it is 120 less 4.5 volts plus 6 volts $= 121.5$ volts, or 1.5 volts higher than at the point of supply.

CHAPTER XV.

ALTERNATING-CURRENT CIRCUITS.

The laws governing the loss of potential in direct-current circuits apply to alternating-current circuits only as regards the loss due to resistance.

In an alternating-current circuit voltage drop is caused by the combined effect of: (*a*) *resistance*, (*b*) *inductance* and (*c*) *capacity*.

The component of drop due to resistance is directly opposed to the current flowing in the circuit, and as in direct-current circuits is $E = CR$.

Inductance. — The component of drop due to inductance is a counter electromotive force set up in the circuit by the current flowing through it. The magnetic field of the circuit, reversing with each alternation, induces an electromotive force in it, which lags a quarter cycle behind the current wave. The resistance drop being directly opposed to the current and the reactance drop being a quarter cycle behind it, their relation may be represented by two sides of a right-angled triangle, as in Fig. 181. The line *OC* represents the resistance drop in 1000 feet of No. 6 wire, and the line *CD* represents the reactance drop in the same length of wire. The resultant *OD* of these two influences is called the *impedance*. The inductance of an

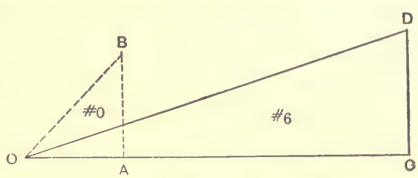


Fig. 181. Resistance and Reactance of No. 6 and No. 0.

electric current varies with the frequency of the current flowing in the circuit and with the number of lines of force linked with the circuit for each ampere of current flowing in it. The reactance of a given circuit is therefore more when it carries current at 60 cycles than at 25 cycles. Similarly, inductance is increased by the separation of the conductors of a circuit or by the introduction of iron into the magnetic field, since either of these increase the number of lines of force linked by the circuit.

For this reason if alternating-current circuits are to be installed in iron pipe, all conductors of the circuit must be carried in the same pipe so that the entire magnetic field will be within the pipe and will not be affected by the presence of the iron. With overhead circuits where there is no iron in the magnetic field, the only means of varying the inductance is by changing the distance between opposite polarities or the frequency, or by coiling the wires.

Calculation of Inductance. — The inductance of a single-phase circuit is $X = \frac{2\,d \times 6.28 \times L \times f}{1000}$ ohms, in which L is the coefficient of self-induction in millihenrys per 1000 feet of wire, f is the frequency and d is the length in thousands of feet.

The coefficient of self-induction of parallel wires of non-magnetic metal, strung in open air and without iron in the magnetic field, may be calculated from the formula

$$L = .14 \log \frac{D - r}{r} + .0152 \text{ millihenry per 1000 feet of wire,}$$

in which D is the distance between centers of the conductors and r is the radius of the conductor.

For a circuit of No. 0 wire strung 12 inches apart,

$$L = .14 \log \frac{12 - .162}{.162} + .0152 = .277 \text{ millihenry.}$$

At 60 cycles,

$$X = \frac{6.28 \times 60\ L}{1000} = .377\ L = .1043 \text{ ohm per 1000 feet of wire.}$$

At 25 cycles,

$$X = \frac{6.28 \times 25\ L}{1000} = .157\ L = .0434 \text{ ohm per 1000 feet of wire.}$$

The reactance at any other frequency is in direct proportion to the ratio of the frequencies.

From the formula for self-induction it is apparent that the effect of the separation of the wires does not vary directly with the distance of separation.

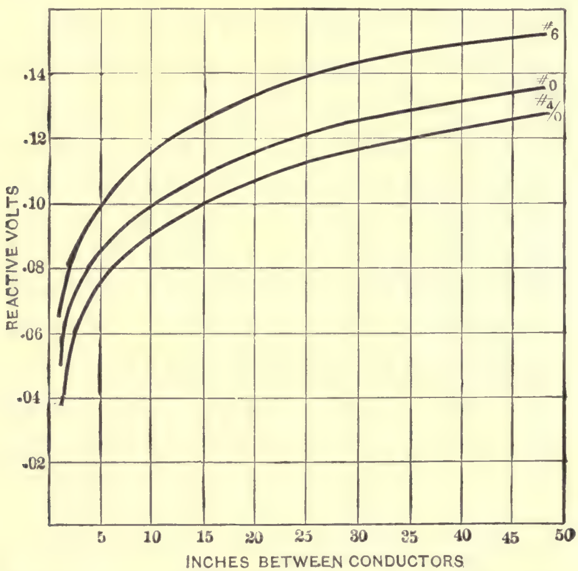


Fig. 182. Relation of Reactance to Separation of Conductors.

For instance, when D is 2 inches the value of $\frac{D - r}{r}$ for No. 0 wire is $\frac{2 - .162}{.162} = 11.3$ and the value of the logarithm is 1.054. At 12 inches, $\frac{D - r}{r}$ is 73.2 and the logarithm is 1.87.

The inductance varies as 1.054 is to 1.87, while the distance has been increased to six times its former values.

The rate of change of the inductance as the distance between centers is varied is shown for a few principal sizes of conductor by the curves in Fig. 182. These are based on the values given in Table XXIII.

TABLE XXIII.—INDUCTANCE PER 1000 FEET OF CONDUCTOR AT 60 CYCLES.

Size.	Volts per ampere. Distance between centers.						Resistance at 68 deg. F.
	¾ in.	1 in.	2 in.	3 in.	6 in.	12 in.	
1,000,000	....	....	......	......	.063	.0784	.01035
500,000	....	....	......	......	.071	.0864	.0207
350,000	....	....	......	......	.0746	.0905	.0296
0000	.0328	.0394	.0553	.0646	.0805	.0964	.0489
000	.0355	.0421	.058	.067	.0832	.0991	.0617
00	.0381	.0447	.060	.070	.0858	.1017	.0778
0	.0408	.0474	.0633	.0726	.0885	.1043	.0981
1	.0435	.0501	.0659	.0752	.0911	.107	.1237
2	.0461	.0527	.0686	.0779	.0938	.1097	.156
4	.0514	.0580	.0739	.0832	.0991	.1150	.248
6	.0567	.0633	.0792	.0885	.1044	.1203	.394
8	.0621	.0687	.0845	.0938	.1097	.1256	.627
10	.0674	.074	.0898	.0991	.1151	.1309	.997

Size.	18 in.	24 in.	36 in.	48 in.	60 in.	72 in.
1,000,000	.0877	.0943	.1036	.1102	.1153	.1194
500,000	.0957	.1023	.1116	.1182	.1233	.1274
350,000	.0998	.1064	.1157	.1223	.1274	.1316
0000	.1057	.1123	.1216	.1282	.1333	.1374
000	.1084	.1150	.1242	.1308	.1360	.1401
00	.1110	.1176	.1269	.1335	.1386	.1427
0	.1136	.1202	.1295	.1361	.1412	.1454
1	.1163	.1229	.1322	.1388	.1439	.1481
2	.1190	.1256	.1348	.1414	.1466	.1507
4	.1243	.1309	.1402	.1468	.1519	.1561
6	.1296	.1362	.1455	.1521	.1572	.1613
8	.1349	.1415	.1508	.1574	.1625	.1667
10	.1402	.1468	.1561	.1627	.1678	.1720

It is to be noted that the reactance increases rapidly as the separation is increased up to six inches and then less and less rapidly as the separation is increased.

This is a fortunate condition for overhead transmission lines operating at high voltages which require large separations between opposite polarities.

It is also fortunate that in underground cables distributing heavy low-potential currents the conductors can be brought close together inside of one lead sheath, thus minimizing the inductive component of line drop.

In the operation of alternating current series arc lighting circuits with extended open loops, trouble is sometimes experienced with excessive induction in telephone circuits which pass through such loops. This trouble is obviated by the use of parallel loops, as described in Chapter I.

The calculation of the inductive drop is not convenient when logarithms are not readily available and is rather laborious in any event. The work is simplified by the use of the values given in Table XXIII, which gives the reactance in volts per ampere for 1000 feet of conductors for the distances of separation and sizes of wire commonly used in transmission and distribution work.

For example, assuming a single-phase circuit 10,000 feet long operating at 60 cycles and carrying a load of 100 amperes, with No. 0 wires 12 inches apart, what are the values of the inductive and ohmic components of the impedance?

The reactance per 1000 feet per ampere for No. 0 wire 12 inches apart is $X = .1043$. The resistance from Table XXIII is .098 ohm per 1000 feet. The inductive component of the impedance of the circuit is

$$X = 2\,d \times C \times .1043 = 2 \times 10 \times 100 \times .1043 = 208 \text{ volts.}$$

The ohmic component is $R = 2 \times 10 \times 100 \times .098 = 196$ volts.

The impedance drop of the circuit is $\sqrt{(208)^2 + (196)^2} =$ 286 volts.

The length of the line *OA* in Fig. 181 is proportional to the resistance component, that of *AB* represents the inductive component and *OB* the resultant of the two. If the circuit were of two No. 6 wires the resistance component would be 788 volts, the inductive component 240 volts, and the impedance drop would be $\sqrt{(788)^2 + (240)^2} = 824$ volts.

This condition is represented by *OC* and *CD* in Fig. 181. It will be seen from these examples that the inductive component of drop in a No. 6 wire is only about 40 per cent greater than that of the No. 0 circuit, although its resistance is nearly four times that of the No. 0 circuit. It is further apparent that the ratio of resistance to inductance decreases greatly as the size of wire is increased. On this account increasing the area of alternating current conductors for the purpose of reducing the pressure drop becomes less effective after the size is increased above the point where the resistance is about equal to the inductance. At 60 cycles this is at about No. 0 for overhead circuits, and at 350,000 to 500,000 c.m. for underground cables. At 25 cycles No. 0000 to 250,000 c.m. may be used for overhead lines, and sizes up to 1,000,000 c.m. are effective in underground cables. For instance, in the 10,000 feet of No. 0 circuit above referred to, the ohmic drop is 196 volts and the inductive component is 208 volts at 100 amperes. If this circuit were required to carry 200 amperes it could be replaced by 4/0 cable or supplemented by the addition of another circuit of No. 0. If a 4/0 circuit were substituted, the ohmic drop would be 196 volts as before, but the inductive drop would be 384 volts. With two No. 0 circuits the drop would remain the same, 196 volts ohmic and 208 volts inductive.

Where the drop can be compensated for properly, or where the circuit is so short that the increased drop is negligible, the larger sizes may be used, but where line drop is the

limiting feature, two or more circuits of the smaller wire are preferable.

Resistance and Inductance Factors. — The *resistance factor* of a circuit is the ratio of its resistance to its impedance. Likewise the *inductance factor* is the ratio of the inductance to the impedance.

In the No. 0 circuit used above, for example, the resistance factor is $\frac{196}{286} = .685$ and the inductance factor is $\frac{208}{286} = .727$.

The resistance and inductance factors of a circuit vary with the size of wire and with the distance of separation. At 60 cycles the resistance factor is the higher for the sizes of conductor smaller than No. 0 and the inductance factor is the higher for the sizes of conductor larger than No. 0.

When the resistance factor is known the inductance factor is $\sqrt{1 - (\text{Resistance factor})^2}$, and *vice versa*. In other words, $(\text{Resistance factor})^2 + (\text{Inductance factor})^2 = 1$.

The power consumed in a circuit is the product of the current by the impedance volts and by the resistance factor. If the loop forming a circuit were closed at the remote end, the power factor of the circuit would be the same as its resistance factor.

The values of inductance factor which correspond to various common values of resistance (or power) factor appear in the following table:

Resistance (or power) factor	50	60	65	70	75	80	85	90	95	97.5	100
Inductance factor	86.6	80	76	71	66	60	53	44	31	22.2	0

Calculation of Line Pressure Drop. — The total pressure drop in a circuit is determined from the resistance and inductance components in conjunction with the power factor of the load which the circuit is carrying. The drop is greatest at power factors which are near the resistance factor of the circuit. If a certain load draws 100 amperes at 70 per cent

power factor over a No. 0 circuit having a resistance factor of 68.5 per cent, the net fall of pressure between the point of supply and point of delivery will be greater than it is with the same current on the circuit at 100 per cent power factor.

Referring to Fig. 183, let the line *OE* represent the pressure delivered at the terminals of an induction motor. *OR* is the component of *OE*, which is doing useful work. *ER* is the wattless component of self-induction which causes the current through the motor to be out of phase with the impressed voltage.

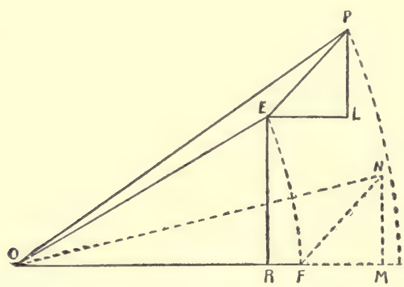


Fig. 183. Effect of Power Factor on Line Drop.

EL is the resistance component and *LP* is the inductive component of the line drop. The resistance component of the line drop *EL* and the power component of the impressed voltage *OR* are in phase with each other and the inductive components *ER* and *LP* are in phase with each other.

The resultant *OP* is the bus pressure necessary to deliver a pressure *OE* at the motor terminals. The net line drop is therefore the difference between *OP* and *OE*.

With noninductive load, such as incandescent lamps, *ER* disappears and the impressed pressure on the lamps takes the position of *OF* (= *OE*). The generated pressure necessary to deliver *OF* at the lamps is *ON* and the drop is the difference between *ON* and *OF*.

For example, assume an inductive load of 100 amperes at 2200 volts single phase, delivered at the end of a two-wire line of No. 0 wire 4500 feet long with wires 12 inches apart, a frequency of 60 and a power factor of 80 per cent. The power factor of the load being 80 per cent, we find by reference to the above table that the corresponding inductance factor is 60 per cent.

$$OR \text{ is } .80 \times 2200 = 1760 \text{ volts.}$$
$$ER \text{ is } .6 \times 2200 = 1320 \text{ volts.}$$

By reference to Table XXIII we find that the resistance drop per 1000 feet per ampere for No. 0 is .098 volt. Hence the resistance drop is $.098 \times 4.5 \times 100 = 44.0$ volts for each wire. There being two wires EL is $2 \times 44 = 88$ volts.

The inductive drop per 1000 feet per ampere for 12-inch centers is .104 volt and LP is $2 \times .104 \times 4.5 \times 100 = 93$ volts. The power and resistance component is $OR + EL$ or $1760 + 88 = 1848$ volts and the inductive component is $ER + LP$ or $1320 + 93 = 1413$ volts.

The resultant of these is

$$OP = \sqrt{(1848)^2 + (1413)^2} = 2332 \text{ volts.}$$

This is the pressure necessary to deliver 2200 volts at the end of the line. The drop is therefore the difference, or 132 volts, with a load of 100 amperes at 80 per cent power factor.

If a lighting load of 100 amperes at 100 per cent power factor were being carried, the inductance factor ER is zero, and ON is

$$\sqrt{(2290)^2 + (93)^2} = 2292 \text{ volts.}$$

The drop is therefore 92 volts, with a load of 100 amperes at 100 per cent power factor.

Mershon Diagram. — The calculations required for the solution of practical problems being rather cumbersome,

Mershon has devised a diagram by which calculations which do not involve charging current may be made with greater facility and yet with sufficient accuracy for all ordinary purposes.

This diagram is presented in Fig. 184 and is based on the principles of the diagram of Fig. 183. The concentric circles are described about a center off the diagram which corresponds to the point O in Fig. 183. The divisions are made in percentages so as to make the scale applicable to all voltages.

The use of the chart may be illustrated by the foregoing circuit of No. 0, carrying a load of 100 amperes at a distance of 4500 feet. The ohmic drop, being 88 volts, is 4 per cent, while the inductive drop is 4.2 per cent. The power factor was assumed at 80 per cent or .8. The base of the .8 power factor line in Fig. 184 is the point *R* in Fig. 183. The point where the .8 power factor line intersects the first circle is the point *E* in Fig. 183. Passing to the right 4 divisions and then up 4.2 divisions a point is reached which is about midway between the 5 per cent and 6 per cent circle. This point is equivalent to the point *D* in Fig. 183. The pressure necessary to deliver 100 per cent pressure at the end of the circuit is 105.5 per cent. The drop is 5.5 per cent of 2200, or 121 volts. The result may be gotten more accurately if desired by multiplying the percentages of drop by two or three before applying them to the diagram, and then dividing the result by the same multiplier. For instance, multiplying by three in this case, the ohmic drop is 12 per cent and the inductive drop is 12.9 per cent. Passing to the right 12.0 divisions and upwards 12.9 divisions, we reach a point corresponding to 17.5 per cent. Dividing by three the drop is 5.8 per cent, or 128 volts, as compared with 132 volts determined by calculation.

If the load on the circuit has a power factor of 100 per cent

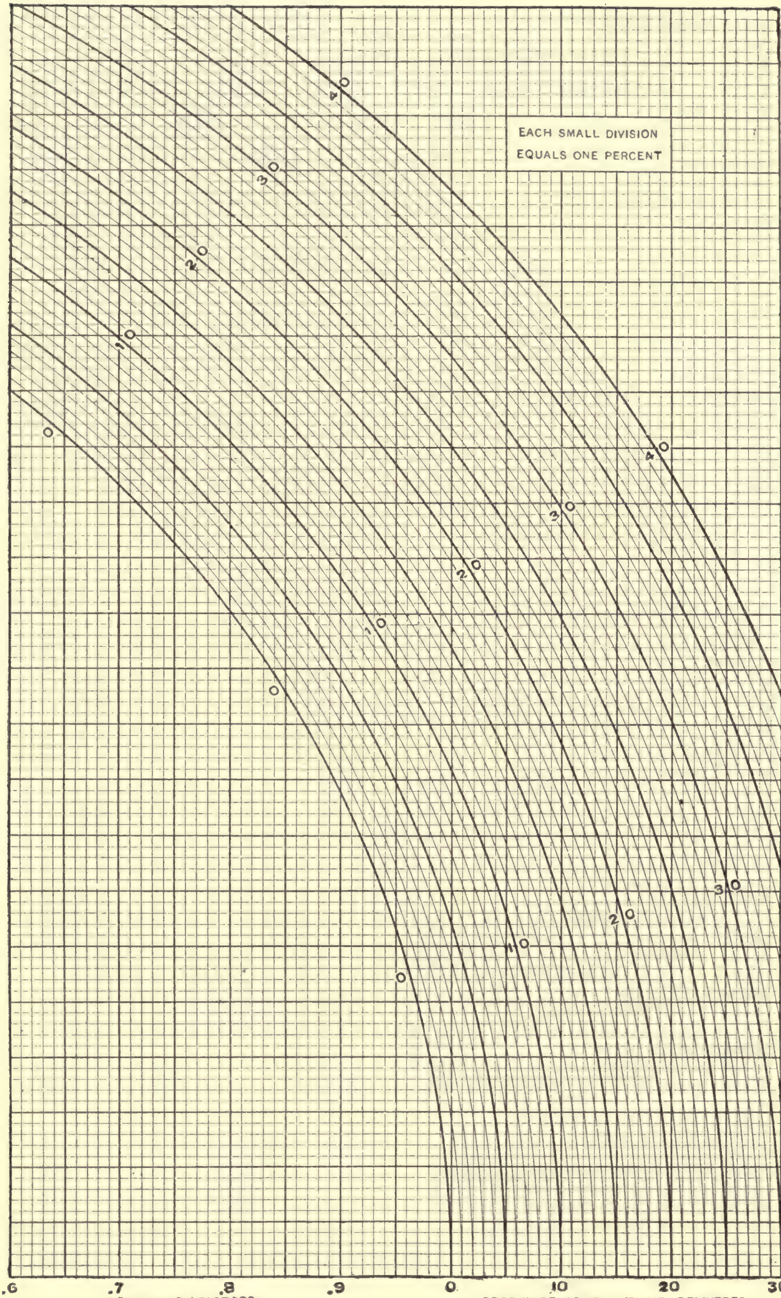


Fig. 184. Mershon Diagram for Calculation of Line Drop. (435)

one begins at the base of the 100 per cent P.F. line, passes to the right 12.0 divisions and up 12.9 divisions. The point is on the 13 per cent circle. Dividing by three the drop is 4.33 per cent, or about 93 volts, as compared with 92 volts calculated.

Two-phase Line Drop. — In the case of a two-phase four-wire circuit the drop is figured for one wire and multiplied by two, as in the case of the single-phase circuit.

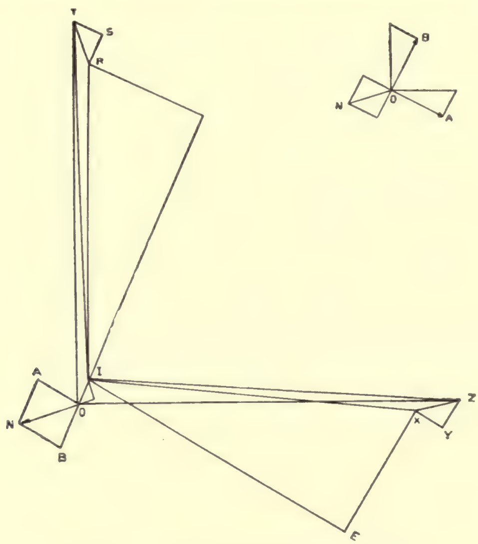


Fig. 185. Drop in Two-phase Circuit.

On a three-wire two-phase feeder, the drop is different on the two phases, even with balanced load since the current in the neutral wire is the resultant of those in the phase wires and the drop on the neutral wire affects the two phases differently. The amount of this difference varies with the power factor of the load, and is, of course, further affected by unbalanced load.

In Fig. 185 the smaller diagram in the upper corner shows

the current relations at a power factor of 90 per cent with balanced load, the current on phase A being OA, that on phase B being OB and that on the neutral conductor being ON. In case of unbalanced load, the neutral current swings around to a position more nearly in opposition to the current on the phase which carries the heavier load.

The drop on each of the wires is determined as it would be for a single wire of a single-phase conduit.

Thus if the circuit is of three No. 0 wires carrying 100 amperes on the phases and 141 amperes on the neutral, the ohmic component of drop on the phase wires at 5000 feet is $100 \times 5 \times .098 = 49$ volts and the inductive component is $100 \times 5 \times .104 = 52$ volts. On the neutral wire this ohmic component is $141 \times 5 \times .098 = 69$ volts and the inductive component is $141 \times 5 \times .104 = 73$ volts.

The relation of these is such that direct calculation of the resultant drop at a given power factor of the load is very complicated. It may, however, be laid out graphically in such a way as to indicate the relation very clearly and to give approximate numerical results. This is done in the larger diagram in Fig. 185.

The current on phase A is represented by OA which is laid out at an angle with OZ corresponding to a power factor of 90 per cent. This is combined with OB the current on B phase to determine the current ON on the neutral conductor.

The drop on the neutral wire is represented by OI, the resultant of the ohmic and the inductive components.

The drop on the phase wire is represented by XZ, made up of the ohmic component XY and the inductive component YZ.

The triangle IEX represents the pressure absorbed by the load at 90 per cent power factor and IX is the pressure delivered at the end of the line. The pressure impressed at the point of supply is OZ and the drop is the difference between OZ and IX.

Similarly the drop on phase B is the difference between IR and OT. It is apparent that these differences are not equal, the drop on A phase being less than that on B phase.

The construction of the diagram is a cut and try process, since the power factor is modified somewhat by the inductive drop of the line wires, and the phase position of OI is shifted somewhat thereby. Fortunately, the use of such a diagram is not necessary where line drop compensators are used in each wire as they make due allowance for changes in balance, changes in load and in power factor. It is only necessary to determine the values of XYZ, RST and OCI at the rated full load of the current transformers supplying the compensator, as described in the chapter on Voltage Regulation.

Drop in Three-phase Circuits. — In a three-phase circuit made up of three conductors symmetrically arranged in a triangle and carrying a balanced load, the inductive effect is the same in each wire and the calculation of drop may be made as easily as for a single-phase circuit.

The ohmic drop in each wire is in phase with its current, but as the current in the three wires are 120 degrees apart the ohmic drop for the two wires making up any phase is not twice that of one wire, as it is in the single-phase circuit, but is 1.73 times this drop. Likewise the inductive component, which is 90 degrees behind the current, is 1.73 times that of a single wire for the loop.

These values are readily found from the figures in Table XXIII, and the known values of current, size of wire and length of circuit. The percentage may then be applied to the Mershon diagram.

For example, if the No. 0 circuit 4500 feet long carrying 100 amperes at 60 cycles and 12 inches separation were a three-wire three-phase circuit, the ohmic drop would be as in the single-phase circuit, $100 \times .098 \times 4.5 = 44$ volts per wire.

The drop in two wires of either phase would be $44 \times 1.73 = 76$ volts. This is $\frac{76}{2200} = 3.4$ per cent.

The inductive component *per wire* is $100 \times .104 \times 4.5 = 47$ volts, and for the loop $47 \times 1.73 = 81$ volts, or $\frac{81}{2200} = 3.7$ per cent.

Applying these percentages to the Mershon diagram we find the drop at 80 per cent power factor is 5 per cent of 2200, or 110 volts.

If the load in kilowatts on the three-phase circuit were the same as on the single-phase circuit, the current per wire on the three-phase circuit would be $\frac{100 \times 1.73}{3} = 58.0$ amperes, and the drop at 58 amperes on the three-phase circuit would be $\frac{58}{100}$ of 5 per cent, or 2.9 per cent.

The single-phase drop at the same load was found to be 5.8 per cent, or twice the three-phase drop.

Therefore for the same load and equal line drop, the size of the conductor in a three-phase circuit may be just half that of a single-phase circuit.

There being three wires in the three-phase circuit, it follows that the weight of copper required for a three-phase circuit is three-quarters of that required for a single-phase transmission, other things being equal.

Therefore, if calculation shows that a certain sized conductor will carry a *given load* at a *given line drop, single phase,* it follows that *three* conductors of *one-half* that size will carry the *same* load at the *same drop, three phase,* if the load is balanced.

Nonsymmetrical Arrangement. — When the arrangement of conductors is not symmetrical, the inductive component is different between different pairs of wires, on account of the different distances between centers. The most common case is that in which the wires are arranged on a cross arm in the same horizontal plane, as is common practice in distribution

circuits, and to some extent in transmission circuits. In such cases the equivalent of a symmetrical arrangement can be secured by transposing the conductors at proper intervals. Fig. 186 shows a circuit transposed at two points, so as to produce a complete spiral of the line. This is not required in 2200-volt distributing feeders which are equipped with line-drop compensators, as the compensation can easily be adjusted to correct unbalanced inductive conditions of this sort.

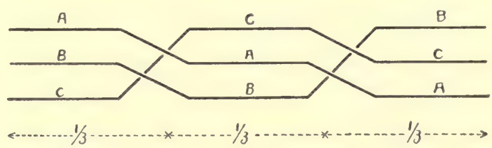


Fig. 186. Transposition of Three-phase Circuit.

Unbalanced Three-wire Three-phase Circuits. — The calculation of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Unbalanced loads which are not more than 10 to 15 per cent from one another may usually be averaged and considered as balanced for practical purposes.

One of the most common conditions of this sort is found in systems where the lighting is all on one phase of the feeder and the third wire carries a small scattered load of three-phase power. Under these conditions the lighting phase may be considered as a single-phase circuit, as the current in the two conductors that make the lighting phase is much greater than it is in the other conductor, and the drop due to the lighting phase current is but little out of phase with the pressure which produces it.

However, as the power load increases the current in the conductors of the lighting phase pulls more and more out of phase with the lighting pressure, and the drop on the lighting phase becomes less and less for a given current value, until finally, when the current on the power phases equals that on

the lighting phase, the drop on the lighting phase is but 86.6 per cent of what it would be with the same amount of current carried as lighting only.

That is if 100 amperes on the lighting conductors produced a drop on the lighting phase of 10 per cent when there is no power load on the feeder, the drop with 100 amperes on each conductor will be only 8.66 per cent.

In practice this relation will not hold exactly, on account of the fact that the power factor of the lighting load is usually 95 per cent or higher, while that of the power load is 75 per cent to 80 per cent. This tends to make the current in one of the lighting phase conductors somewhat lower and that in the other lighting phase conductor somewhat higher than it would be if the power factor were the same in all phases. However, the reduction in the drop on the lighting phase is not sufficient ordinarily to interfere with the regulation of the lighting phase until the current on the power conductor reaches a point where it is more then 30 per cent of the average current on the lighting conductors.

Four-wire Three-phase Line Drop. — The working pressure at the receiving devices in such systems is the star pressure, that is, the pressure between phase wires and neutral. When the star pressure is 2200 volts, the pressure across phase wires is $2200 \times 1.73 = 3800$ volts.

With balanced load the neutral conductor carries no current and the drop is that in the phase wire only. The drop at 100 amperes on a No. 0 circuit 4500 feet long is $100 \times 4.5 \times .098 = 44$ volts. This is 2 per cent of 2200 volts. Likewise the inductive component is $100 \times 4.5 \times .104 = 47$ volts, or 2.1 per cent. At 80 per cent power factor, by the Mershon diagram the drop is 3 per cent.

As in the balanced three-wire circuit the size of wire for a given load and drop is just *half* what it would be for a *single-*

phase circuit, and the *distance* may be halved and the calculation made as for a single-phase circuit if desired.

In the case of an unbalanced four-wire circuit, which is the more usual condition, the effect of the drop on the neutral wire must be taken into consideration. This varies with the proportion of unbalance and requires a graphical solution.

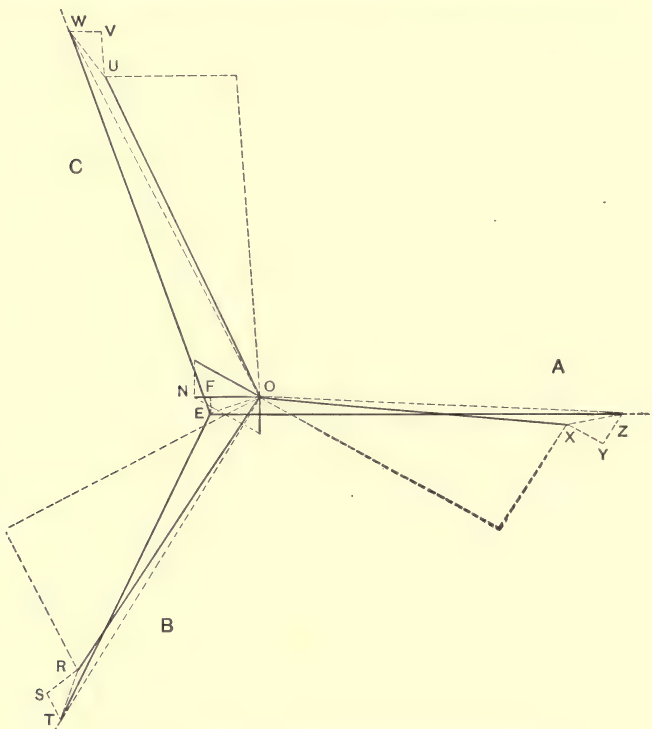


Fig. 187. Drop on Three-phase Four-wire Circuit.

In general the effect of the unbalance is to increase the drop on the more heavily loaded phases and to make it less than it would be at balanced load on the lighter loaded phases.

The proportions of the diagram, Fig. 187, are based on calculations for a circuit having an ohmic drop of 15 per cent,

an inductive drop of 10 per cent and loads on the three phases in the ratio of 60, 80 and 100, on A, B and C respectively.

The current ON on the neutral conductor is the resultant of an unbalance of 20 on B and 40 on C. This fixes the phase of the neutral current and hence of the drop in the neutral conductor. The triangle OEF represents the ohmic and inductive components of the neutral drop.

The drop on the phase wires is represented by the triangle at the outer ends of the phase vectors. These are proportional to the drop in the phase conductor (single distance only). The vector sum of the phase drop and of the neutral drop is the total loss of pressure at the end of the circuit. For instance, the net drop on A phase is the difference between the impressed pressure EZ and the delivered pressure OX. Similarly the drop on B phase is $ET-OR$, and that on C phase is $EW-OU$.

Where line-drop compensators are employed in each conductor the only calculations required are those for the four individual conductors, and the use of a diagram to get the combined effect is unnecessary. The importance of equipping the neutral conductor with a line-drop compensator is readily apparent from the diagram.

It is difficult to get accurate results from the diagram except when drawn to a large scale, and as the phase of the neutral current shifts hourly with different conditions of balance it is impossible to properly regulate unbalanced four-wire circuits by a schedule of volts and amperes, as is sometimes done with single-phase circuits.

Mutual Induction. — Where several alternating-current circuits are carried on the same poles there is an inductive reaction between them which is proportional to the current flowing and depends on the relative proximity of the circuits. That reaction is known as *mutual induction*, as the current in one circuit affects the voltage on the other, and *vice versa.*

Mutual induction is a magnetic effect of the same nature as self-induction. The magnetic field due to the current in circuit A sets up an electromotive force in circuit B which is proportional to the volume of current in circuit A and the distance between them. Circuit B's field affects circuit A's pressure likewise. The electromotive force of mutual induction is a quarter cycle behind the current which produces it, and its phase must be taken into account in determining the effect.

The mutual induction voltages are so small at the ordinary current values at primary distributing voltages that they can be neglected, but where distribution is effected by means of circuits operating at voltages less than 300 which involve heavy currents, mutual induction is likely to be very troublesome. Its effect can be largely offset by making the distance between circuits as large as possible and by so arranging the conductors that as little of the magnetic flux of one circuit may be linked with another as possible. Circuits may also be transposed at intervals, so that the mutual induction set up in one part of the circuit is offset by the mutual induction in the opposite sense in another section of the circuit.

With three-phase circuits this should be done twice, so as to make a complete spiral turn of the three wires.

The effect of a transmission line on a telephone circuit run parallel to it is usually such that numerous transpositions must be made in the telephone circuit to prevent inductive disturbances which make the telephone line noisy.

Underground circuits run in separate ducts are not usually sufficiently affected to make any appreciable disturbance.

Skin Effect. — Another condition which affects the pressure drop on alternating-current circuits is known as the *skin effect.* This is found in cables of large cross-section and is due to the fact that the currents passing through the strands around the outer surface of the cable induce a pressure in the

strands near the center which opposes the flow of current and causes the outer strands to carry the greater part of the load of the cable. In very large cables the current in the center strands is found to be so small that it is desirable to build up large cables about a core of nonconducting material. This puts the working metal near the outer layer and makes a more economical cable. Cables over 500,000 c.m. are often made in this manner where they are to be used on 60-cycle current, and over 1,000,000 c.m. on 25 cycles.

The rule for the calculation of the skin effect is a quite complicated one, as it involves the frequency, area of conductor, permeability of metal, temperature coefficient, etc. It is sufficient for all practical purposes to know that the skin effect is proportional to the product of the frequency by the circular mils. The higher this product, the more the resistance of the cable is increased by the skin effect. The resistance factors corresponding to various values of circular mils and frequency are given in Table XXIV. To determine the skin effect of a cable having an area of 1,000,000 c.m., carrying current at 60 cycles, refer to Table XXIV opposite the product 60,000,000. The resistance factor is 1.096. The resistance of 1,000,000 c.m. cable to direct current at 68 degrees F. being .0103, the effective resistance is .0103 × 1.096 = .01129 when the cable

TABLE XXIV.—SKIN-EFFECT COEFFICIENTS.

Cir. mils × frequency.	Coefficient.		Cir. mils × frequency.	Coefficient.	
	Copper.	Aluminum.		Copper.	Aluminum.
10,000,000	1.000	1.000	80,000,000	1.158	1.069
20,000,000	1.008	1.000	90,000,000	1.195	1.085
30,000,000	1.025	1.006	100,000,000	1.23	1.104
40,000,000	1.045	1.015	125,000,000	1.332	1.151
50,000,000	1.07	1.026	150,000,000	1.433	1.206
60,000,000	1.096	1.04	175,000,000	1.53	1.266
70,000,000	1.126	1.053	200,000,000	1.622	1.33

carries alternating current at a frequency of 60 cycles. The resistance drop is increased 9.6 per cent by the skin effect in this size of cable.

Electrostatic Capacity. — Alternating-current circuits are subject to electrostatic-capacity phenomena which have an important bearing at the higher transmission voltages and frequencies. A line is charged and recharged with each alternation of the voltage. A charging current flows in such a circuit, which is proportional to the rate of change of the impressed voltage. The rate of change being greatest when the electromotive force wave is passing through zero, the charging current is at its maximum at that instant, and therefore is one-quarter cycle ahead of the impressed voltage wave. The charging current is a half cycle ahead of the inductive component, which is a quarter cycle behind the voltage wave, and therefore tends to neutralize the effect of self-induction. At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered.

At transmission voltages and distances it becomes a matter of considerable importance in some cases.

The charging current of a circuit varies with its electrostatic capacity, its length and the voltage and frequency at which it is operated.

The capacity of an overhead circuit is fixed by the distance between the conductors and by their size. With insulated conductors surrounded by a lead sheath, the capacity is further affected by the dielectric constant of the insulating material.

The capacity of a single-phase circuit strung in the open air per 1000 feet of circuit is $C = \dfrac{.003677}{\log \dfrac{D}{r}}$ microfarads, when D is the distance between centers of conductors and r is half

the diameter of the conductor. The logarithm is the common logarithm.

Calculation of Charging Current. — The charging current of a single-phase circuit is $I = \frac{6.28\, dfCE}{1,000,000}$ amperes, when d is the distance in thousands of feet, f is the frequency, C is the capacity and E is the voltage between conductors.

For example, in a circuit consisting of two No. 0 B. & S. wires strung 60 inches apart, 200,000 feet in length and operated at 40,000 volts, and 60 cycles, the charging current would be

$$I = \frac{6.28 \times 200 \times 60 \times C \times 40,000}{1,000,000} \text{ amperes.}$$

$$C = \frac{.003677}{\log \frac{D}{r}} = \frac{.003677}{\log \frac{60}{.162}} = .00143,$$

whence

$$I = \frac{6.28 \times 200 \times 60 \times .00143 \times 40,000}{1,000,000} = 4.3 \text{ amperes.}$$

The charging current of a three-phase circuit is $\frac{2}{\sqrt{3}}$ times that of a similar single-phase circuit at the same voltage and frequency.

That is, if the No. 0 circuit above referred to were a three-phase circuit operating at 40,000 volts with conductors equally spaced, the charging current would be

$$I = \frac{2 \times 4.3}{1.73} = 4.96 \text{ amperes.}$$

The ratio of $\frac{2}{\sqrt{3}}$ is 1.155, and it is therefore useful to bear in mind the fact that the charging current of a three-phase circuit is 15.5 per cent greater than for a similar single-phase circuit.

The charging current of 4.96 amperes on the three-phase line would require $\frac{4.96 \times 3 \times 40{,}000}{1.73 \times 1000} = 344$ kv-a. of generator capacity to charge the line when no load was being delivered.

When an inductive load is being delivered the lagging component of the load tends to offset the leading current required to charge the line. In this case it would require a lagging component of 344 kv-a. to bring the power factor to 100 per cent.

An inductive load of 80 per cent power factor has a 60 per cent inductance factor. 344 is 60 per cent of 573 kv-a. Hence an inductive load of 573 kv-a. at 80 per cent power factor at the point of delivery would produce a power factor of 100 per cent at the generating station.

The line current leaving the generating station under these conditions would be about 80 per cent of that entering the step-down transformers at the point of delivery. The line drop is therefore somewhat less than it would be without the charging current, and somewhat greater than it would be if the power factor were 100 per cent at both ends of the line. At higher power factors the wattless current is a smaller proportion and the load required to bring the power factor up to 100 per cent at the generator is greater. The charging current per 1000 feet of wire at 1000 volts three-phase line pressure is given in Table XXV for 60 cycles. The values at other voltages or frequencies are proportionately higher. At 40,000 volts, the values in the tables should be multiplied by 40, or at 25 cycles they are $\frac{25}{60}$ of those in the table.

The tendency of the charging current to raise the power factor of the line current tends to reduce the line drop where the load is of an inductive character. With very long lines and high voltages, it is not unusual to have a line charging current so high that the power factor is a leading one most

TABLE XXV.—CHARGING CURRENT THREE-PHASE CIRCUITS IN AIR.

Size of conductor.	Amperes per 1000 feet, per 1000 volts, at 60 cycles. Distance between centers.						
	¾ in.	1 in.	24 in.	36 in.	48 in.	60 in.	72 in.
350,000	......	......	.000867	.000788	.000745	.00071	.000688
0,000	.00312	.0025	.000819	.000749	.000710	.000679	.000658
000	.00284	.00233	.000797	.000732	.000693	.000666	.000645
00	.0026	.00216	.000775	.000714	.000679	.000649	.000632
0	.00241	.00202	.000758	.000701	.000662	.000640	.000618
1	.00224	.0019	.000740	.000684	.000649	.000623	.000605
2	.00209	.0018	.000719	.000666	.000636	.00061	.000592
4	.00185	.00161	.000688	.000640	.00061	.000588	.000571
6	.00165	.00146	.000645	.000605	.000575	.000557	.000544
8	.00150	.00134	.000623	.000579	.000557	.000540	.000523
10	.00137	.00124	.000597	.000562	.000536	.000523	.000510

of the time. With an 80-mile line operating at 60,000 volts, 60 cycles, it requires an inductive load of about 2800 kv-a. at 80 per cent power factor to neutralize the line charging current. At loads less than 3000 kv-a. the power factor would be leading and the inductive component of the line drop would tend to raise the power factor. The charging current of long high-voltage lines places restrictions upon the size of the generating and transforming equipment in some cases. For instance, a generating station supplying an 80-mile 60,000-volt line should not have a generator rated at less than 1500 to 2000 kv-a., as the line charging current is about 1600 kv-a. and it would be impossible to excite the line at full pressure from a smaller machine running singly without overloading it.

Charging Current of Cables. — In underground cable work the effect of charging current is greatly increased by the reduced separation of polarities while the inductive effect is correspondingly decreased thereby. The charging current cannot be determined so easily, however, as in the case of the overhead line, since the dielectric in the cable is not air and

the dielectric constant of the insulation must be taken into account. The formula for the capacity of a three-phase three-conductor cable in one lead sheath is more complex than that for overhead lines. The capacity per 1000 feet of cable is

$$C = \frac{.00735\,K}{\log \dfrac{3\,a^2\,(R^2 - a^2)^3}{r^2\,(R^6 - a^6)}} \text{ microfarads,}$$

when K is the dielectric constant, a is the distance from the center of the cross-section of the cable to the center of the conductors, R is the radius of the inside of the lead sheath and r is the radius of the conductor.

The charging current is $I = \dfrac{2 \times 6.28\,fCEL}{1.73 \times 1{,}000{,}000}$, as in the case of the three-phase overhead line.

Dielectric Constants. — The value of K, the dielectric constant in such calculations, must be determined experimentally by tests on samples of cable. It varies with different materials and with variation of temperature with the same material. In paper cable the different oils used to impregnate the paper are likely to have different constants.

The value of the dielectric constant of air is 1, that of vulcanized rubber is 3.5, manila paper, dry, is 1.8, manila paper and resin oil is 2.4, and varnished cambric is 3.5. The effect of temperature on the three principal kinds of cable insulation is shown in Table XXVI. This table contains coefficients by which the value of dielectric constants should be multiplied as the temperature rises above 60 degrees F. The general effect of increase in temperature is to decrease the dielectric constant and therefore the charging current.

The length and voltage of cable systems is usually such that the charging current is not sufficient to cause any operating inconvenience. In the 25-cycle 9000-volt system of the

TABLE XXVI.—VARIATION OF DIELECTRIC CONSTANT WITH TEMPERATURE.

	Temperature coefficients.							
Temperature F.	60	70	80	90	100	110	120	140
Oiled paper......	1.00	.89	.75	.60	.46	.34	.25	.14
Varnished cloth .	1.00	.90	.79	.70	.60	.50	.42	.31
Rubber	1.00	.97	.93	.89	.84	.80	.76	.66

Chicago central station company the charging current of the three-conductor 4/0 cable is about .24 amperes per mile per conductor, or 24 amperes per 100 miles. This amounts to $\frac{24 \times 9000 \times 3}{1.73 \times 1000} = 370$ kv-a. per 100 miles.

With 20,000-volt 60-cycle cables the charging current is about four times that of the 25-cycle cable above cited and its effect becomes noticeable in a large system.

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